Heavy quarkonia production in p+p, d+A and A+A collisions at RHIC

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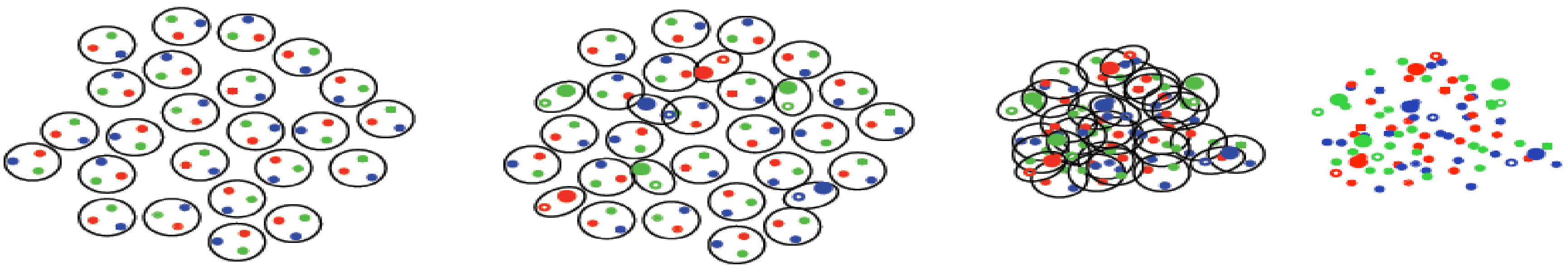
Introduction

Quark Gluon Plasma in Heavy Ion collisions

Qualitatively:

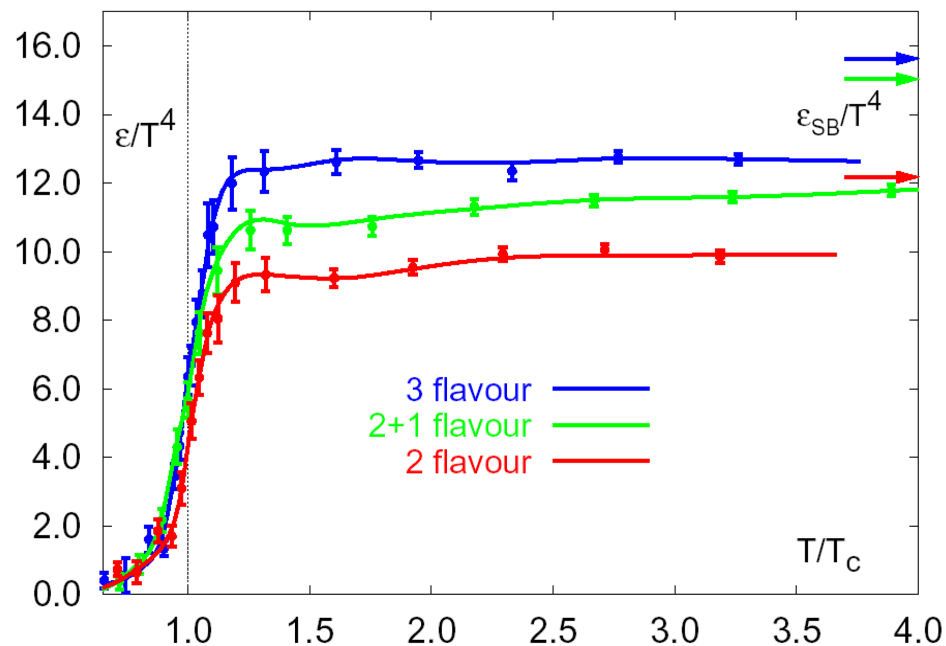


Normal nuclear matter　　Heating　　Compression　　Deconfinment

Lattice QCD calculations:

Number of degrees of freedom in nuclear matter vs Temperature

Exhibits a critical temperature T_c above which quarks and gluons are the correct degrees of freedom that describe the medium



Heavy quarkonia in HI collisions (1)

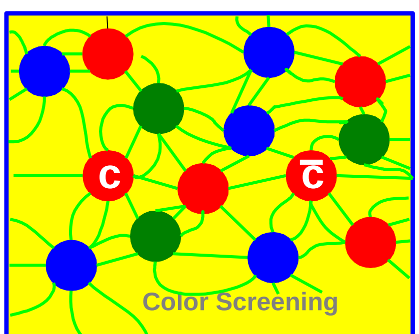
Heavy quarkonia (J/ψ, ϒ) are good candidates to probe the QGP in heavy ion collisions because:

- they have large masses and are (dominantly) produced at the early stage of the collision, via hard-scattering of gluons.
- they are strongly bound (small radius) and weakly coupled to light mesons.

	mass	radius
J/ψ	3.1 GeV	0.50 fm
ϒ	9.5 GeV	0.28 fm

Sensitive to the formation of a quark gluon plasma via color screening:

PLB 178, 416 (1986)



State	J/ψ	ϒ
T_{dis}	1.2 T_c	2 T_c

T_c: QGP formation temperature
T_{dis}: quarkonia dissociation temperature

Heavy quarkonia in HI collisions (2)

However:

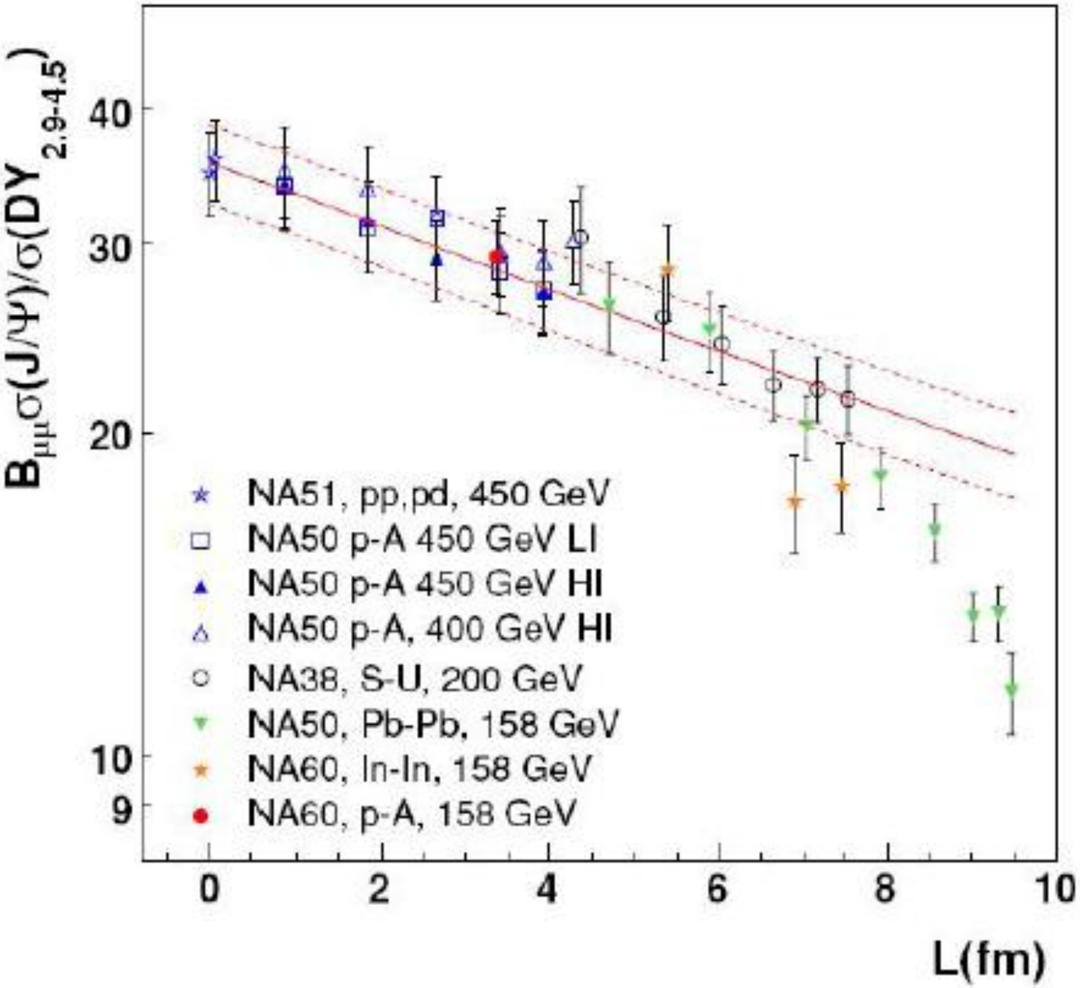
1. Although heavy quarkonia are hard probes, the production mechanism (in p+p) in not well understood;
2. There are many effects that can alter this production in presence of normal nuclear matter (in e.g. p(d)+A);
3. It is unclear how to extrapolate, and subtract these effects from what is measured in A+A, to single-out QGP effects.

Still:

As a resonance, heavy quarkonia are *easy* to measure (and separate from background) as opposed to most other hard probes (photons, open heavy flavors, jets)

J/ψ production at SPS

PLB 410, 337-343 (1997)



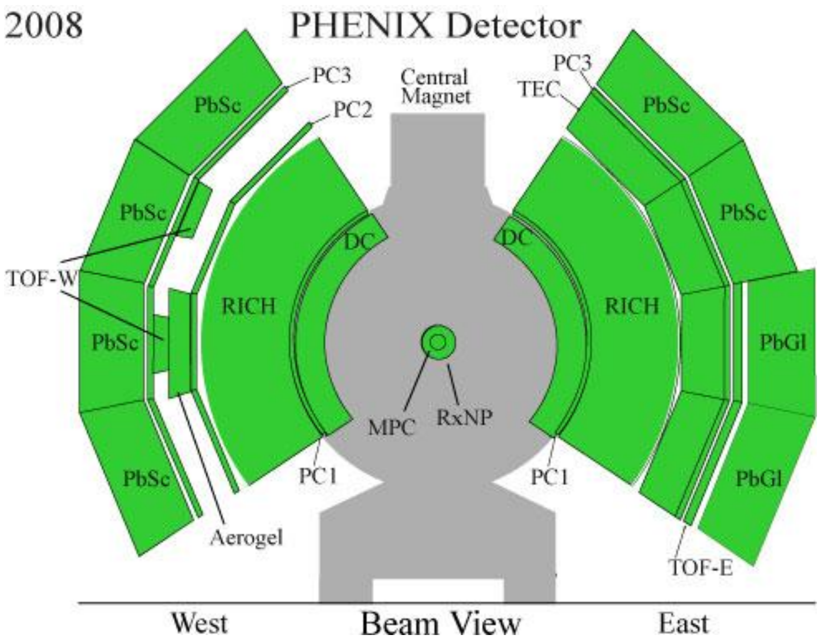
L is the J/ψ path length through the nuclear matter.
Used to compare the results with various colliding nuclei.

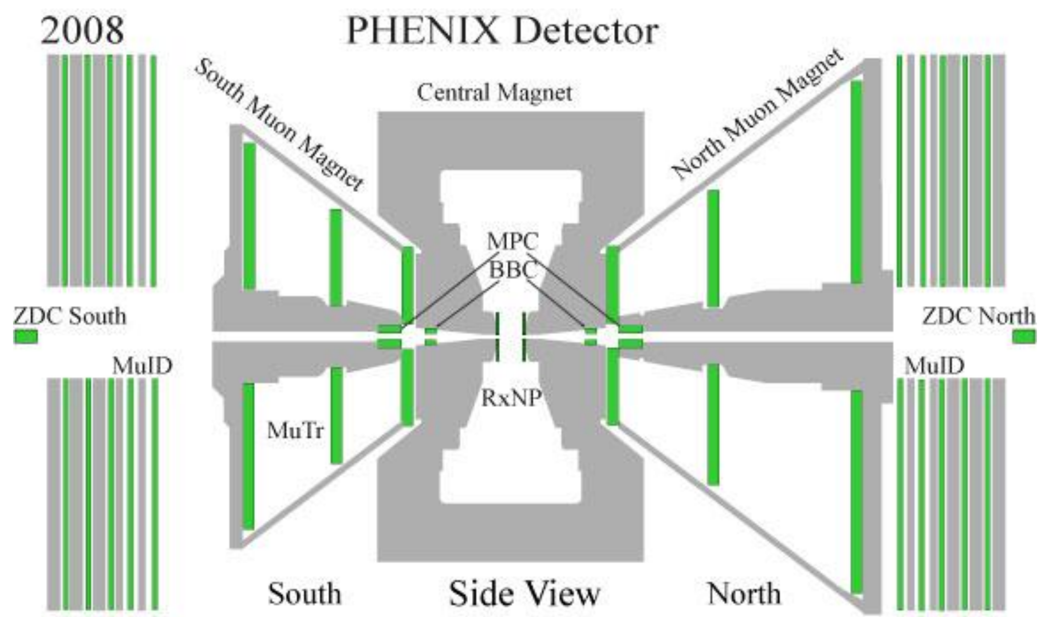
L < 7: suppression is observed due to cold nuclear matter effects (mostly nuclear absorption)

L > 7: an additional suppression is observed.

What happens at higher energy (x10), at RHIC ?

Heavy quarkonia measurements in PHENIX





Mid rapidity: J/ψ,Υ→ e^+e^-
|η|<0.35, ΔΦ= 2 x π/2, p>0.2 GeV/c

Forward rapidity: J/ψ,Υ→ $\mu^+\mu^-$
1.2<|η|<2.2, ΔΦ=2π, p>2 GeV/c

Electrons identified using RICH and EMCAL; tracked using pad and drift chambers

Muons identified using layered absorber + Iarocci tubes; tracked using 3 stations of cathode strip chambers, in radial magnetic field

Outline

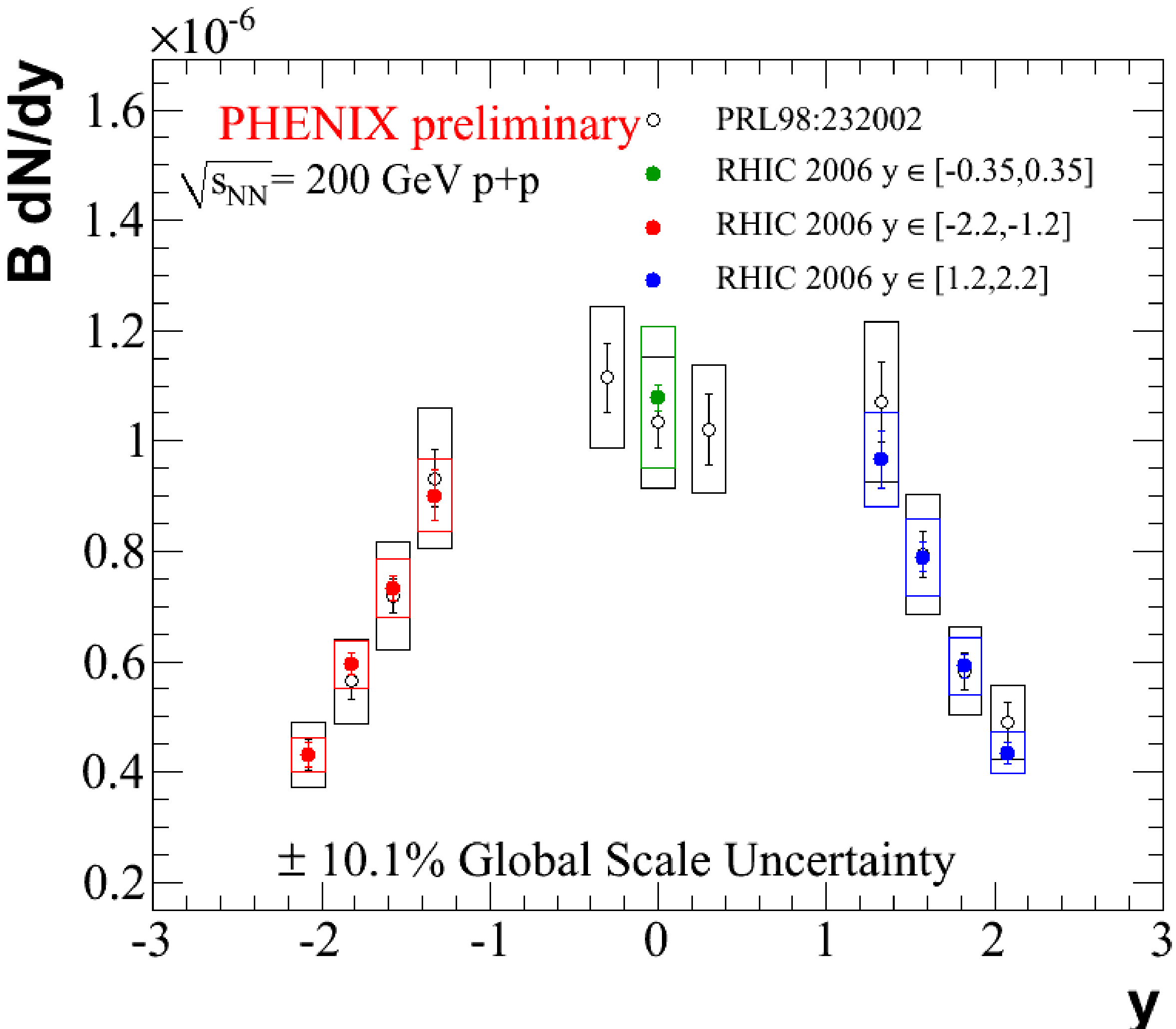
- p+p collisions:
  production mechanism
  baseline for heavy ions

- d+Au collisions:
  cold nuclear matter effects

- Cu+Cu and Au+Au:
  hot nuclear matter effects

I. p+p collisions:
- production mechanism
- baseline for d+A and A+A collisions

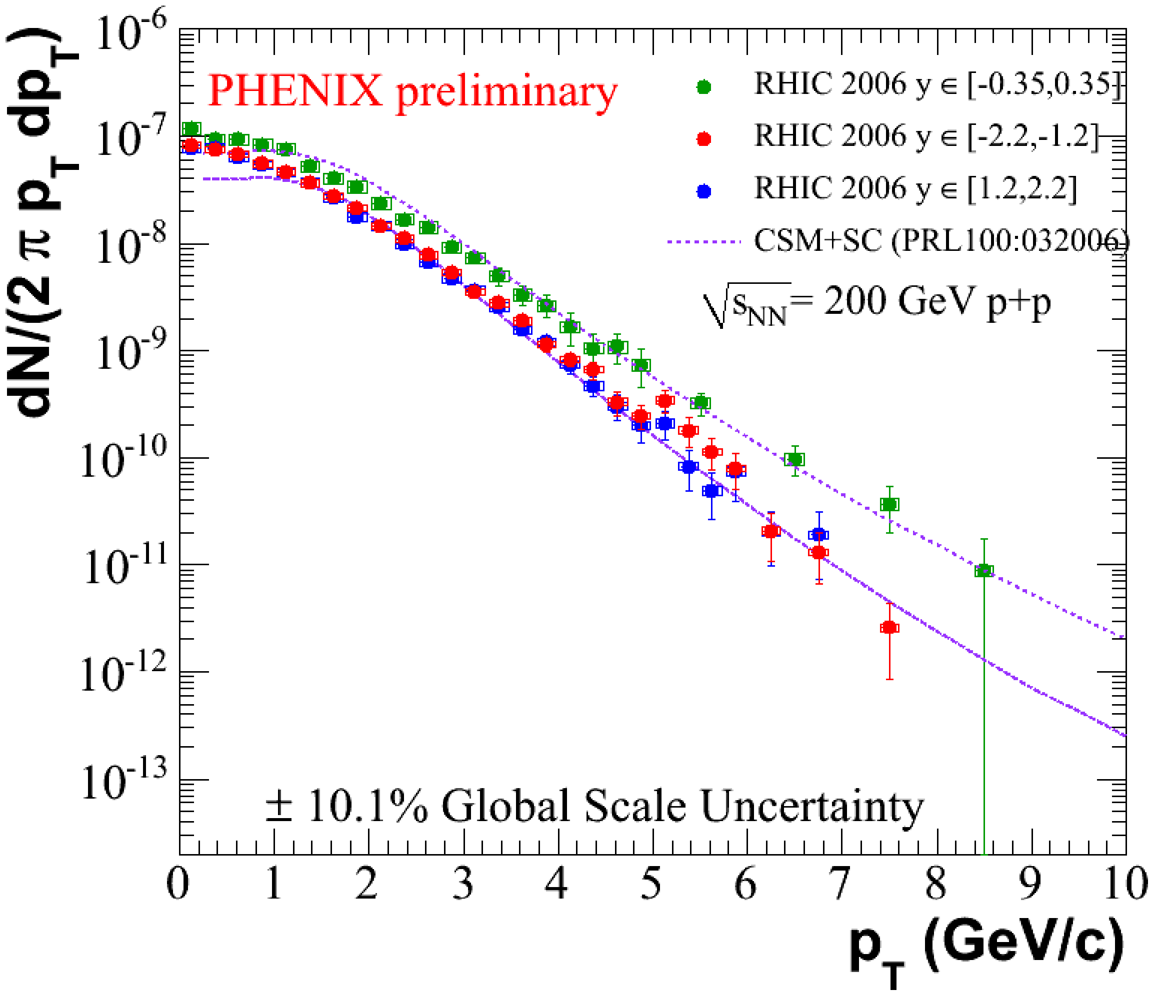
J/ψ measurements (1)



Higher statistics and better control over systematics
Excellent agreement with published results

⇒ Better constraints on models

J/ψ measurements (2)



Excellent agreement between data at positive and negative rapidity

Harder spectra observed at mid-rapidity.

Production mechanism

Several models available, that differ mainly on how the $c\bar{c}$ pair formed during the initial parton scattering (gg at RHIC) is neutralized prior to forming the J/ψ

- **Color Evaporation Model (CEM)**

  Heavy quarkonia production is considered proportional to the $c\bar{c}$ cross-section. The proportionality factor is fitted to data. It is independent from p_T and rapidity.

- **NRQCD, or Color Octet Model (COM)** NLO, NNLO*

  the $c\bar{c}$ pair can be produced in an octet state. The neutralization is realized non-perturbatively via exchange of multiple soft gluons, that do not affect the initial $c\bar{c}$ kinematics.

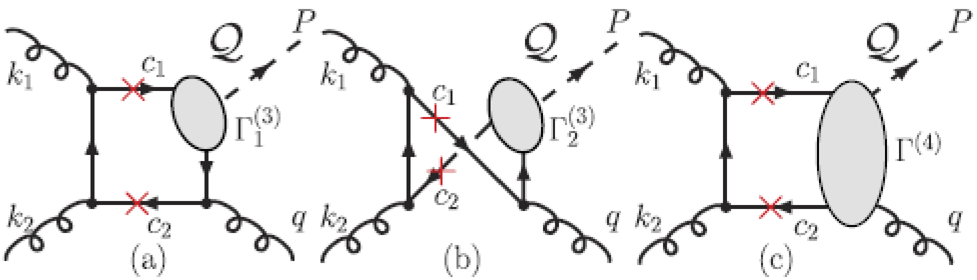
- **Color Singlet Model (CSM)** NLO, NNLO*

  at LO, a third hard gluons is use to neutralized the $c\bar{c}$ pair.

Production mechanism (2)

Recent developments on CSM

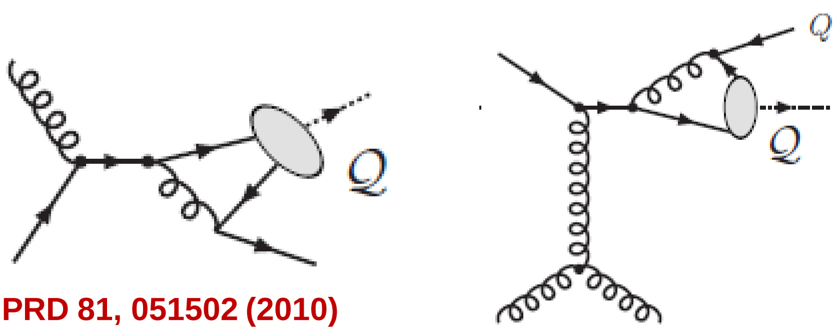
- **s-channel cut:** allow the $c\bar{c}$ pair to be off-shell, prior to interaction with the 3rd hard gluon



PRL 100, 032006 (2008)

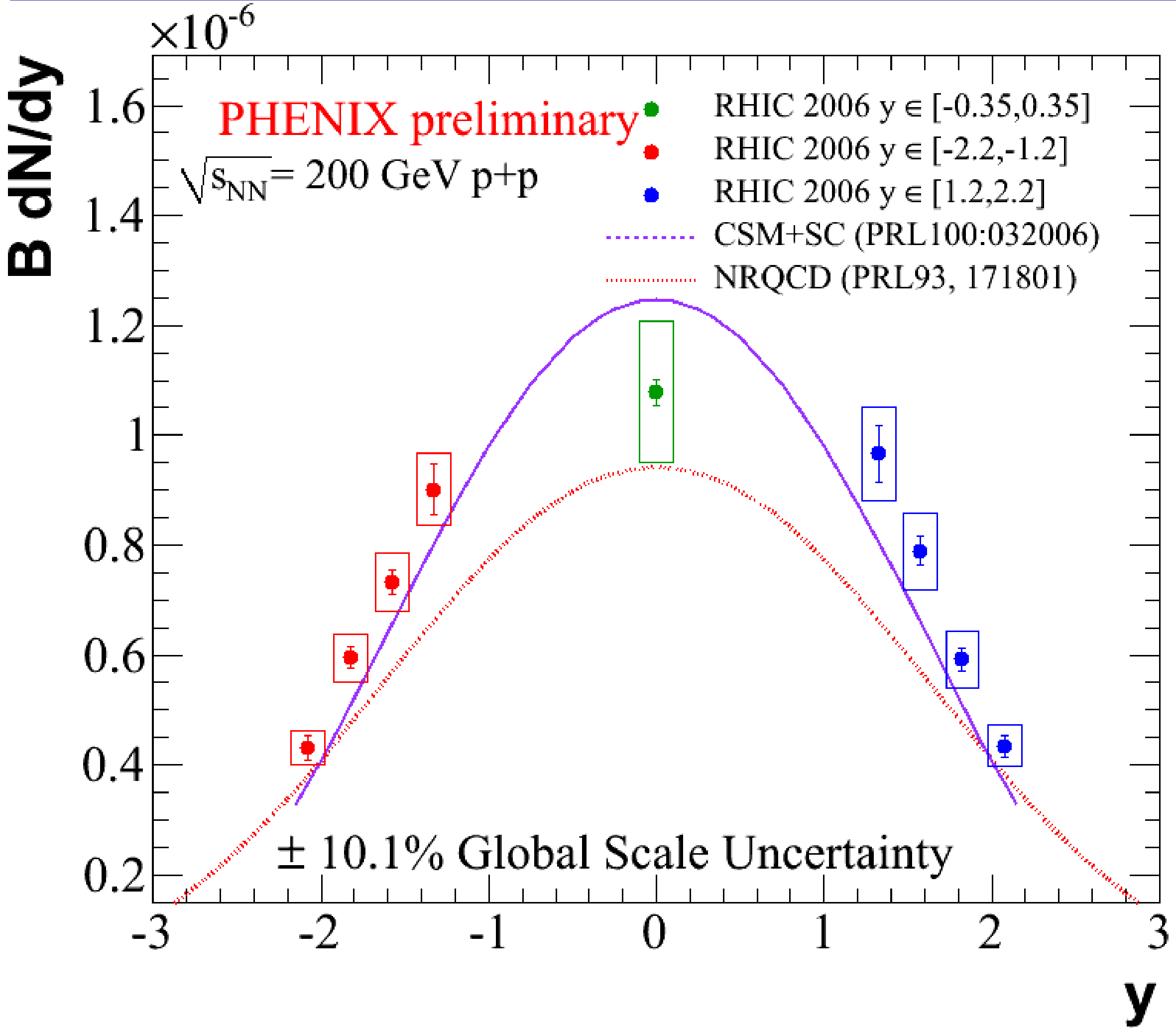
- **CSM at LO, NLO (@RHIC), NNLO* (@Fermilab)**

- **Accounting for J/ψ production from "intrinsic" charm (taken from one of the incoming protons)**



PRD 81, 051502 (2010)

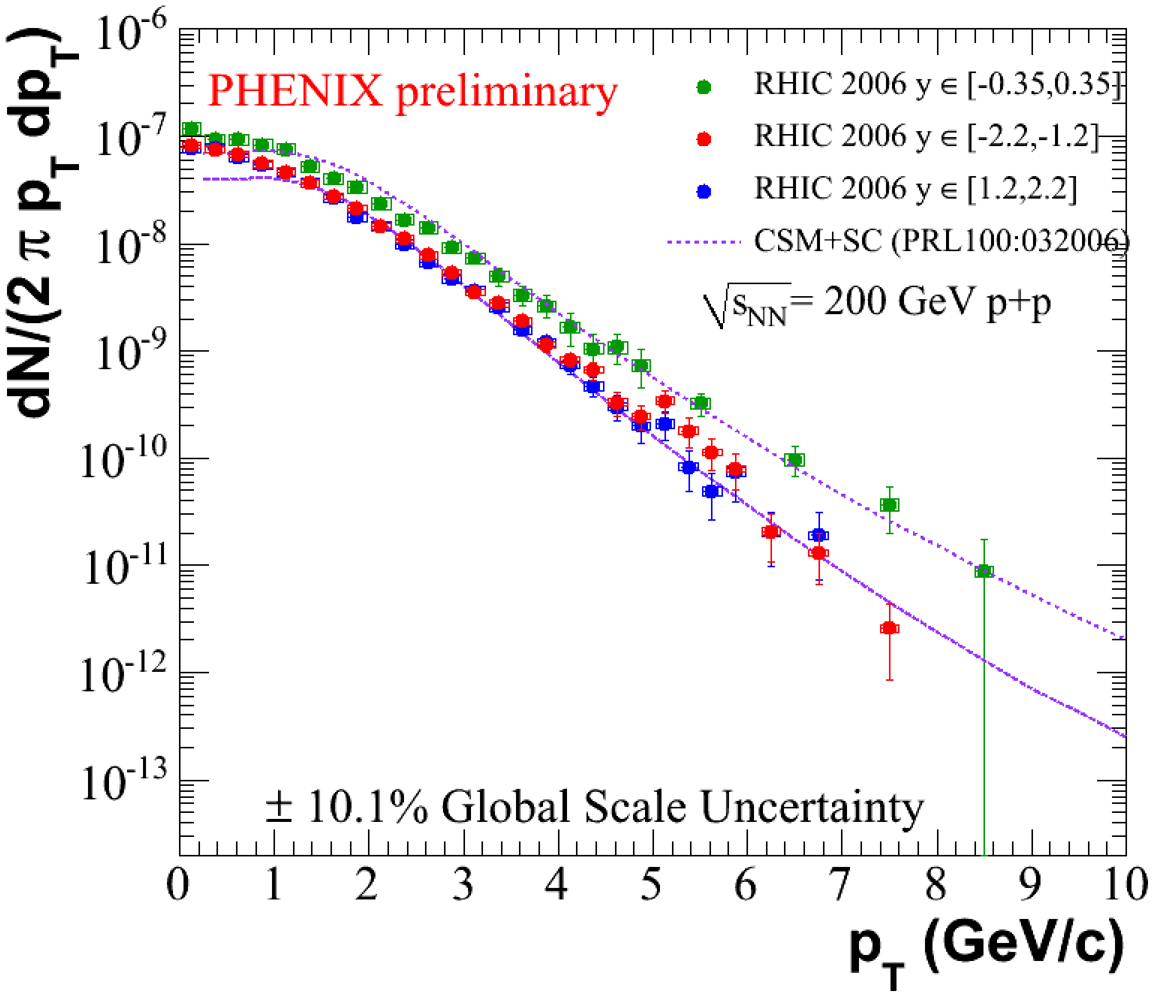
Comparison to models



Models have absolute normalization; they are not scaled to the data.

CSM (LO)+S channel cut, tuned (parametrized) to CDF, does a fairly good job at reproducing PHENIX data.

Comparison to models



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Very good agreement also achieved vs p_T.

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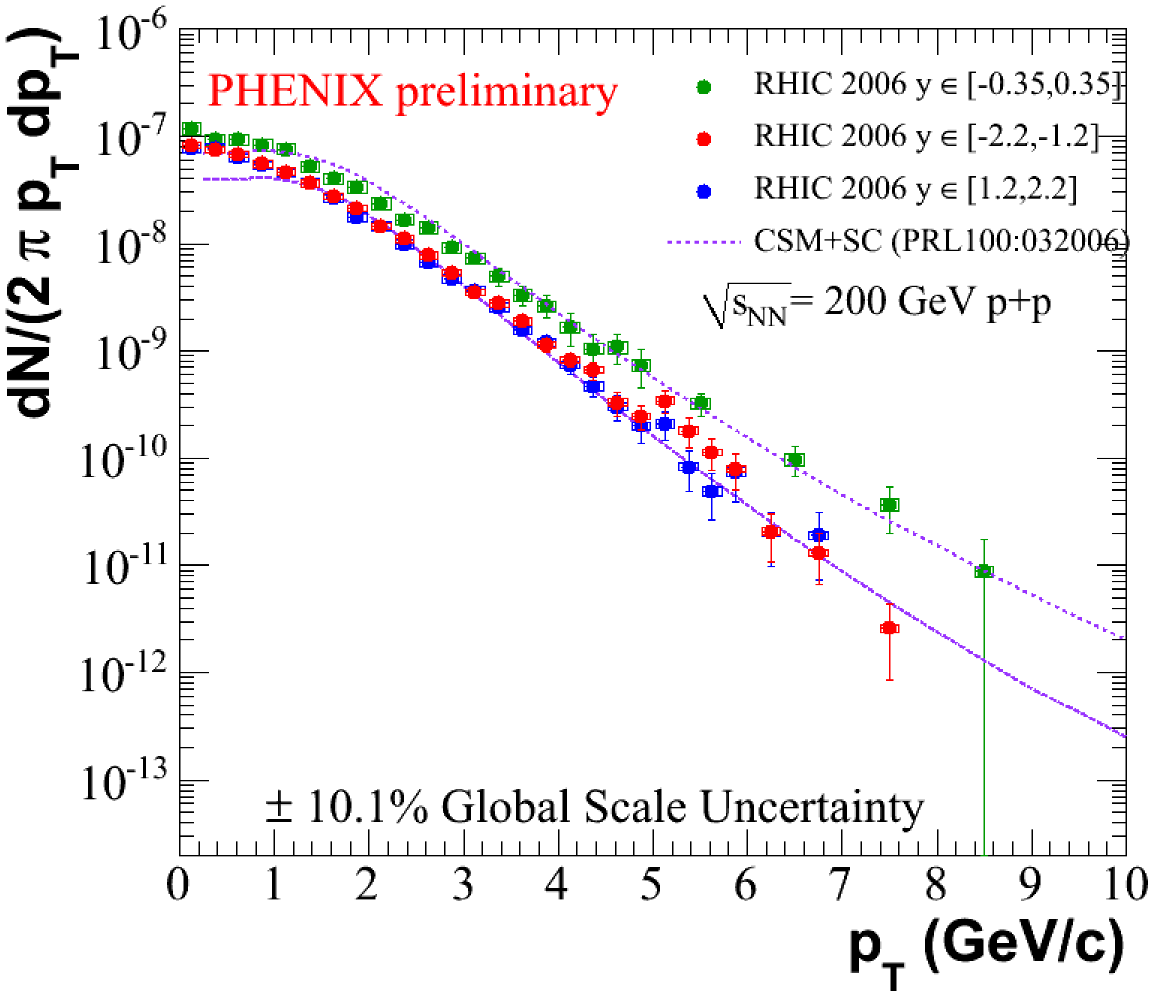

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CSM (LO)+S channel cut, tuned (parametrized) to CDF, does a fairly good job at reproducing PHENIX data.

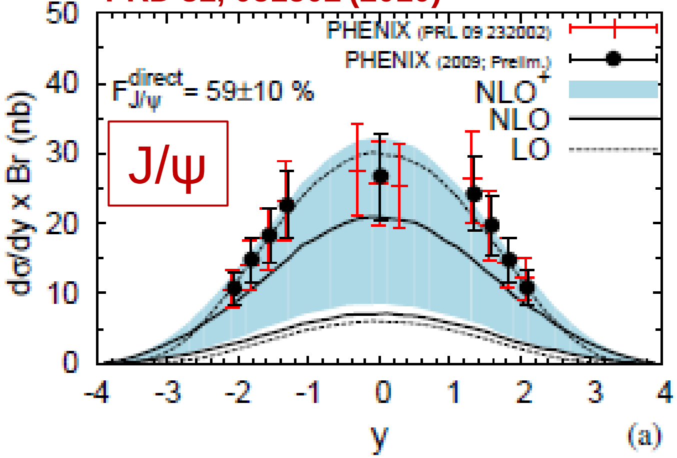
Very good agreement also achieved vs p_T.

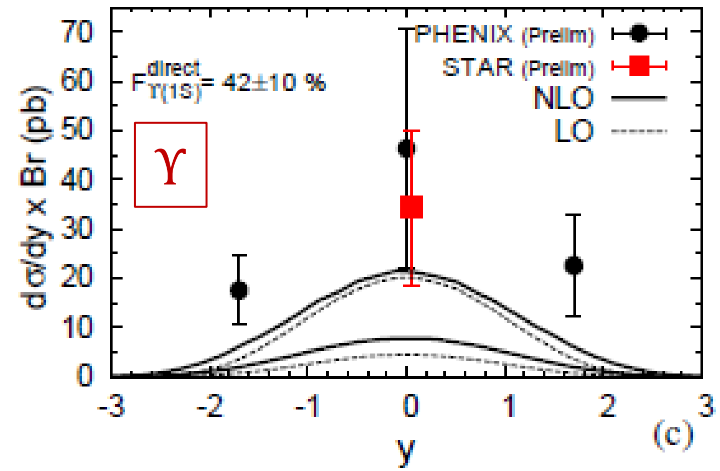
However there are concerns about the validity of s-channel cut approach and the magnitude of the obtained contribution

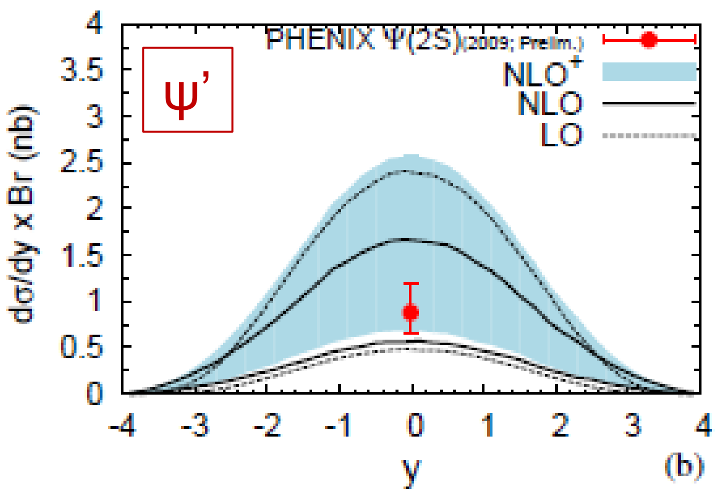
PRD 80, 034018 (2009)

CSM at NLO + Intrinsic Charm

PRD 81, 051502 (2010)







PHENIX J/ψ data are scaled down by ~60% to remove decay contributions.

Only p_T integrated calculations are available.

NLO contribution is negative and smaller than LO. Allows reduction of the theoretical uncertainty.

IC contribution is of the same order as NLO gluon fusion, with opposite sign.

p+p summary

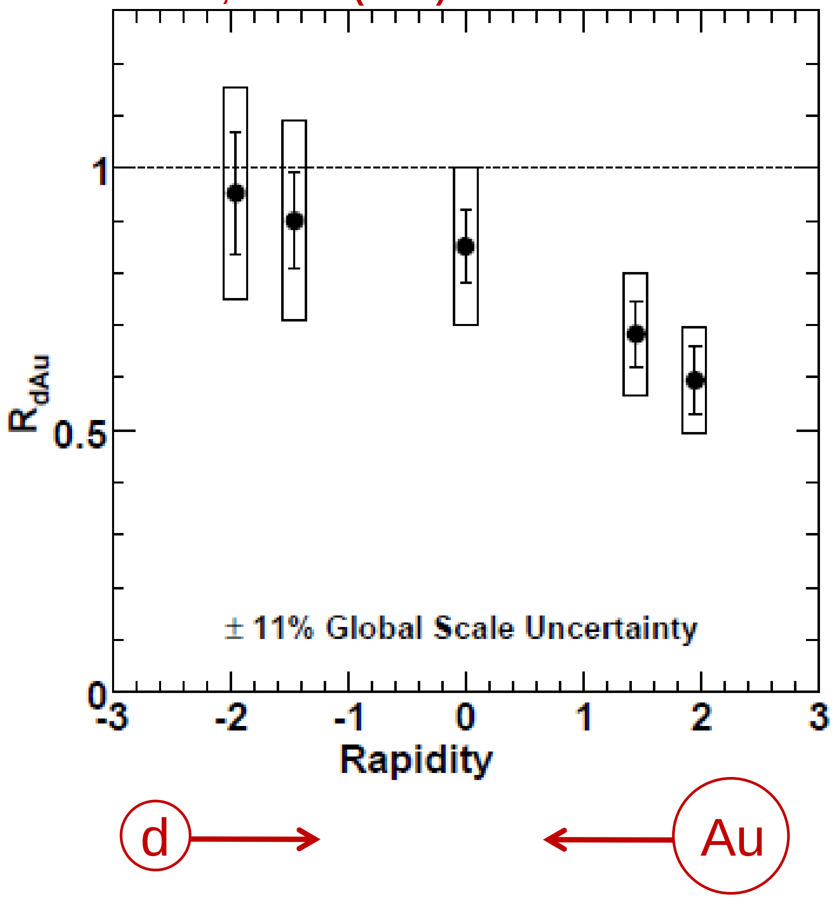
Progress are being made

- on the experimental side, to provide more precise data, and more observables:
  other resonances;
  heavy quarkonia *polarization* (not discussed here)
- on the theoretical side, to have calculations at higher orders; to include more contributions; and to simultaneously describe (and/or fit) multiple observables at different energies

II. d+Au collisions:
Cold nuclear matter effects

J/ψ production in d+Au (1) 2003 data

PRC 77, 024912 (2008)



Nuclear modification factor:

$$R_{dA} = \frac{\text{yield in dA}}{N_{coll}.\ \text{yield in pp}}$$

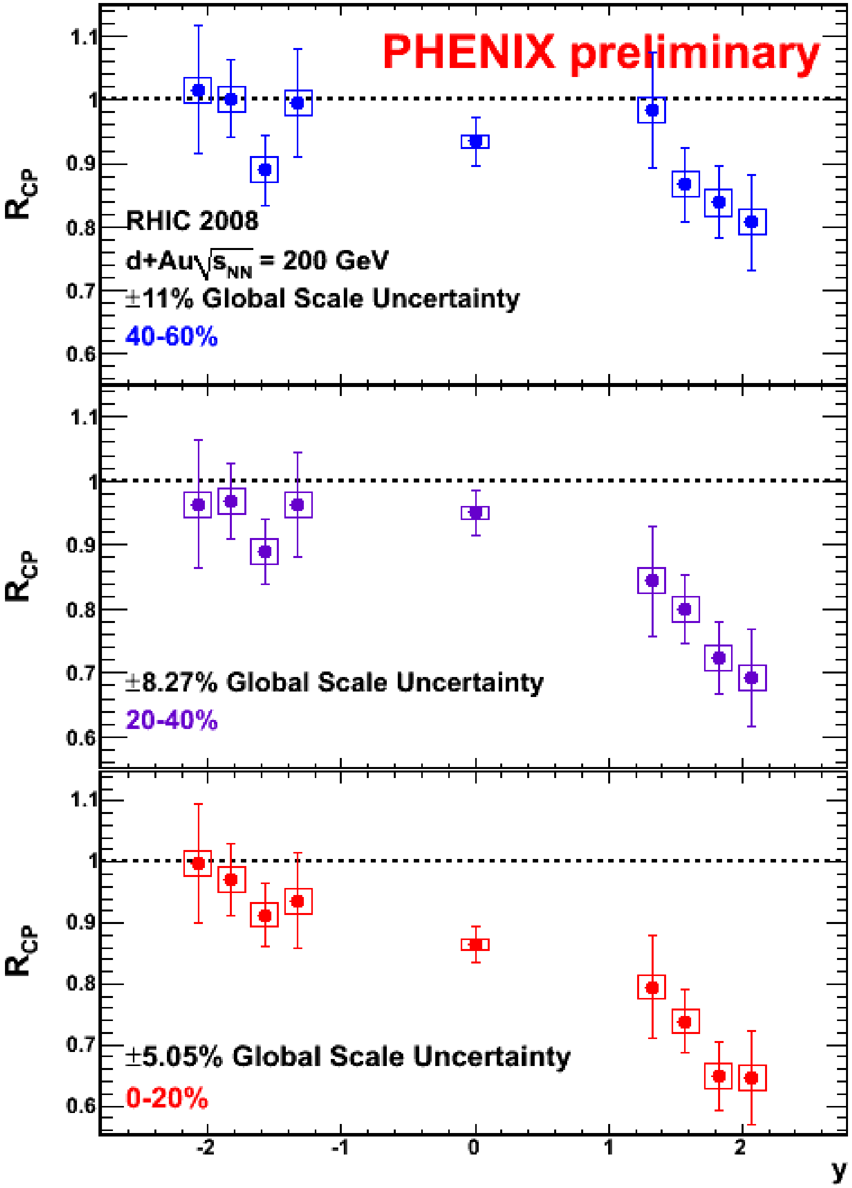
N_{coll}: number of equivalent p+p collisions for one d+Au collision at a given centrality

y<0: Au going side. Large x in Au nuclei (x_2)

y>0: deuteron going side. Small x in Au nuclei (where shadowing is expected)

At forward rapidity, J/ψ production in d+Au differs from scaled p+p

J/ψ production in d+Au (2) 2008 data



2008 d+Au data sample = ~40 times more statistics than 2003 published results.

Enough statistics to provide 4 different centrality bins and 9 rapidity bins.

$$R_{CP}^{0-20\%} = \frac{N_{inv}^{0-20\%} \Big/ \left\langle N_{coll}^{0-20\%} \right\rangle}{N_{inv}^{60-88\%} \Big/ \left\langle N_{coll}^{60-88\%} \right\rangle}$$

Systematic errors largely cancel in R_{cp}.

R_{cp} ~1 at negative rapidity
R_{cp} < 1 and decreases with centrality at positive rapidity

Cold nuclear matter effects (CNM)

Anything that can modify the production of heavy quarkonia in heavy nuclei collisions (as opposed to p+p) in absence of a QGP

Initial state effects:
- Energy loss of the incoming parton
- Modification of the parton distribution functions (npdf)
- Gluon saturation (CGC)

Final state effects:
Dissociation/breakup of the J/ψ (or precursor $c\bar{c}$ quasi-bound state)
Modeled using a break-up cross-section $\sigma_{breakup}$

Modified PDF (npdf)

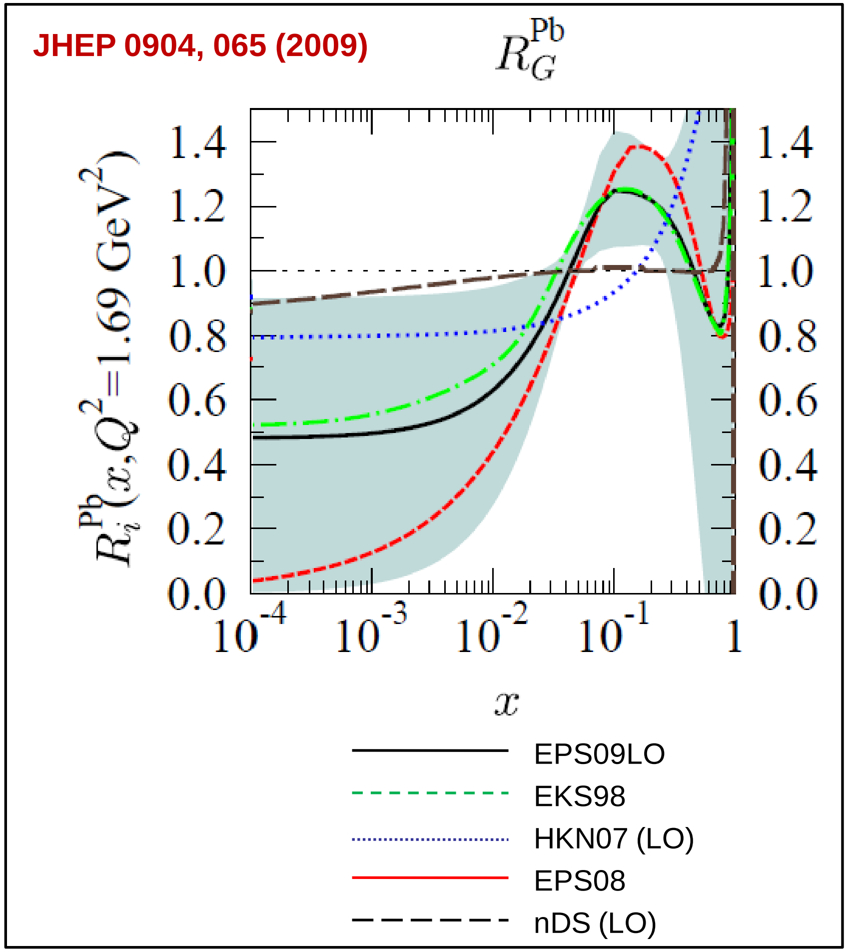
npdf refer to the fact that parton distributions (as a function of x_{bj}) inside a nucleon differ whether the nucleon is isolated or inside a nuclei.

Gluon nuclear npdfs are poorly known, especially at low x (shadowing region).

Various parametrizations range from

- little shadowing (HKN07, nDS, nDSg)
- moderate shadowing (EKS98, EPS09)
- large shadowing (EPS08)

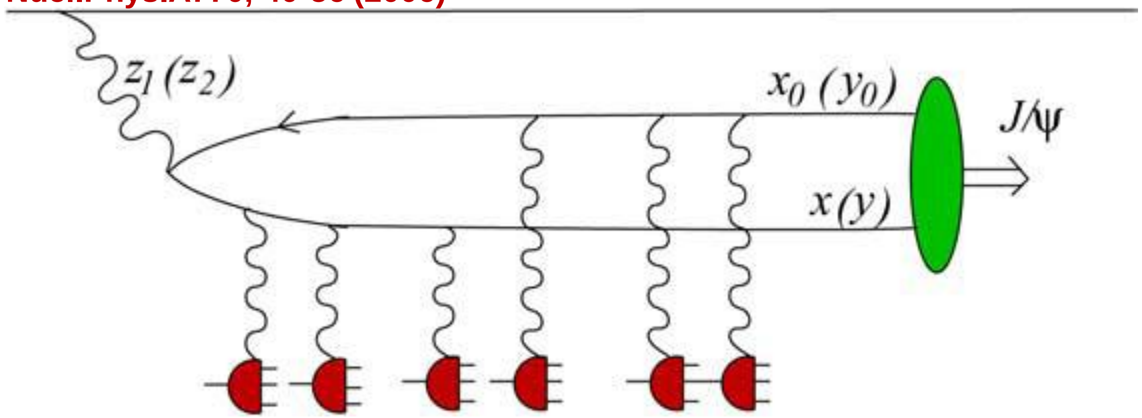
Grayed area correspond to uncertainty due to limited data available for constrain.



Gluon saturation

Provides a different picture of the dAu collision and how J/ψ is produced:

Nucl.Phys.A770, 40-56 (2006)



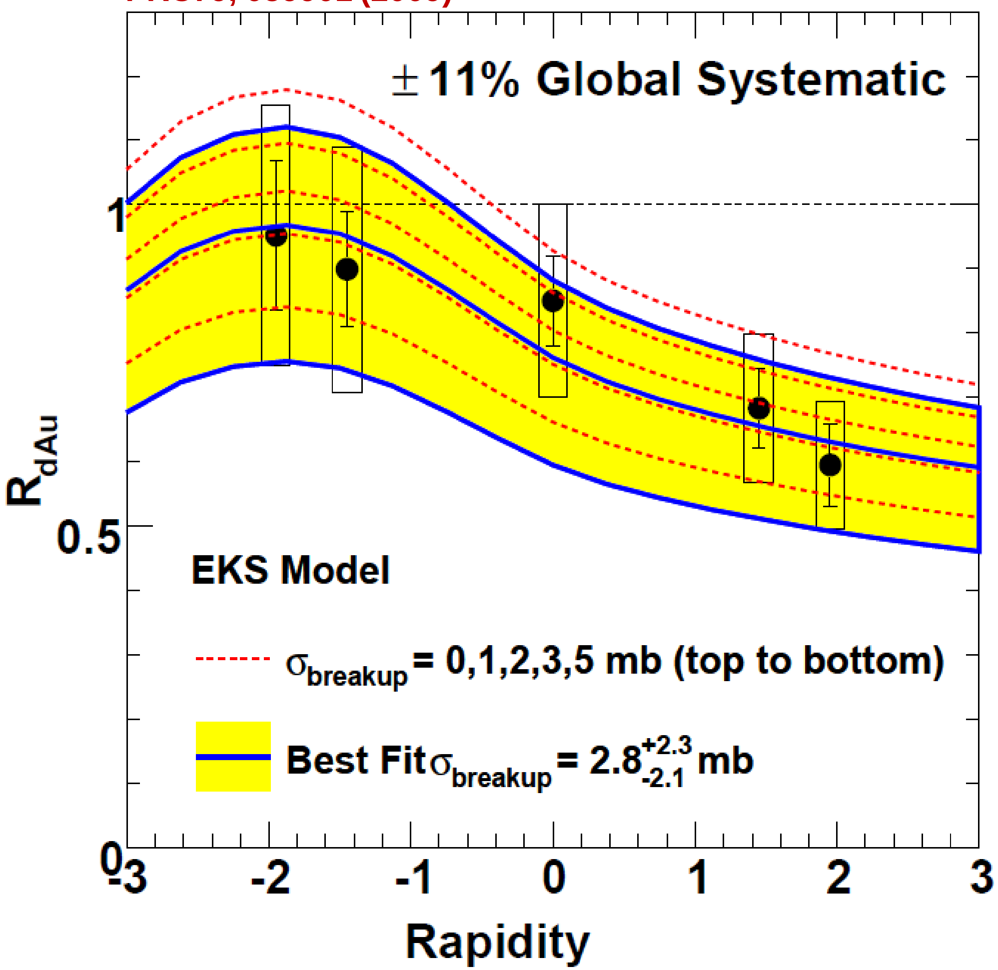
At low enough x_2 (in the target nuclei), the gluon wave functions overlap. The $c\bar{c}$ pair from the projectile parton interacts coherently with all nucleons from the target, resulting in the J/ψ formation.

This is applicable at low x_2 (forward rapidity) only;

makes the use of $\sigma_{breakup}$ irrelevant in this regime.

npdf + $\sigma_{breakup}$ vs (2003) data

PRC79, 059901 (2009)



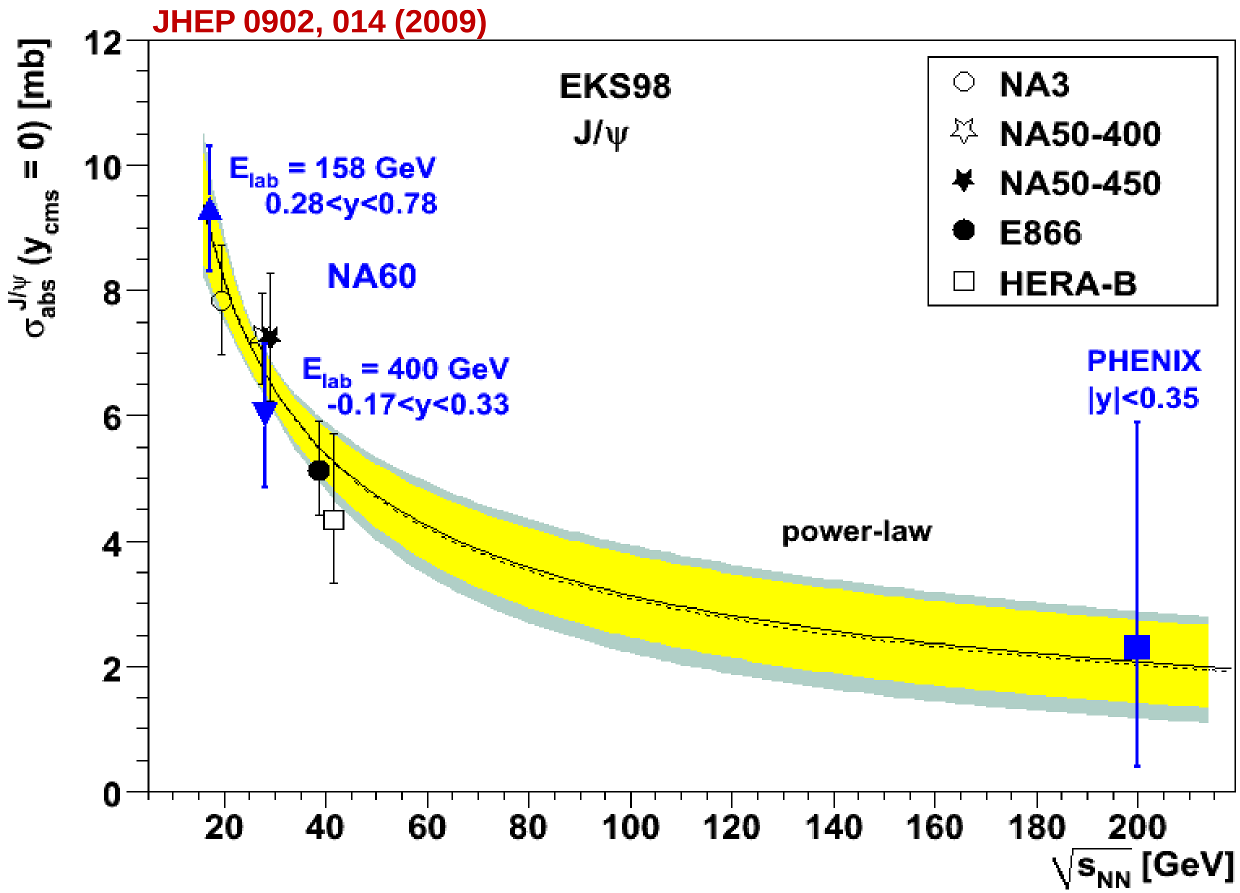
Take a npdf prescription (here EKS)

add a J/ψ (or precursors) breakup cross-section $\sigma_{breakup}$

Fit the best $\sigma_{breakup}$ to the data, properly accounting for correlated and uncorrelated errors.

Here a unique cross-section is used across the entire rapidity range

Energy dependence of $\sigma_{breakup}$ (1)



Putting $\sigma_{breakup}$ as a function of $\sqrt{s}$ and comparing to other experiments shows some sort of global trend, yet to be explained theoretically.

npdf + $\sigma_{breakup}$ vs (2008) data

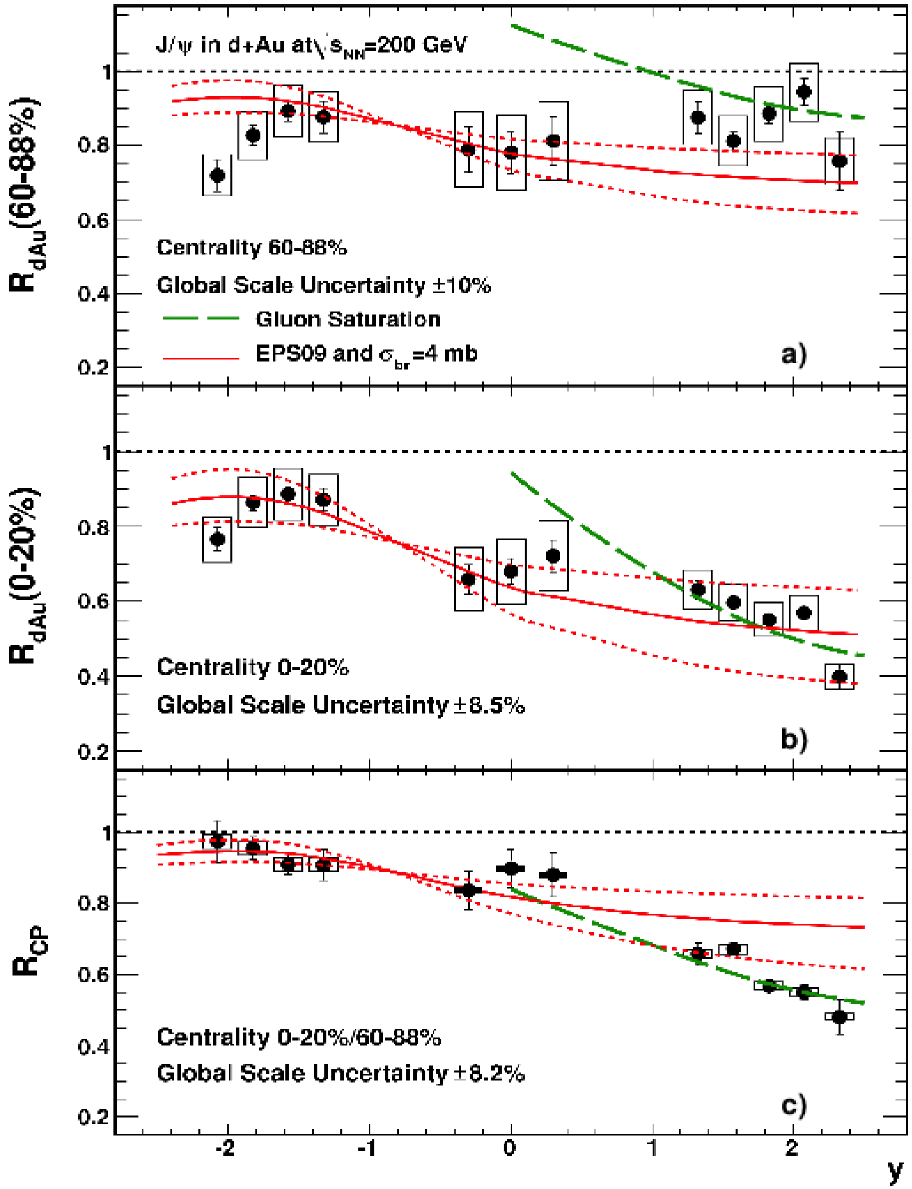
Same exercise as with the 2003 data:

- Take an npdf prescription (here EPS09)
- Add a breakup cross-section
- Make predictions as a function of centrality
- Compare to (more precise) 2008 data.

At forward rapidity, this approach cannot describe both the peripheral and the central data.
This is best illustrated by forming the ratio of the two (Rcp)

On the other hand, data are reasonably well reproduced at forward rapidity by CGC for all centralities.

arXiv:1010,1246 (2010)



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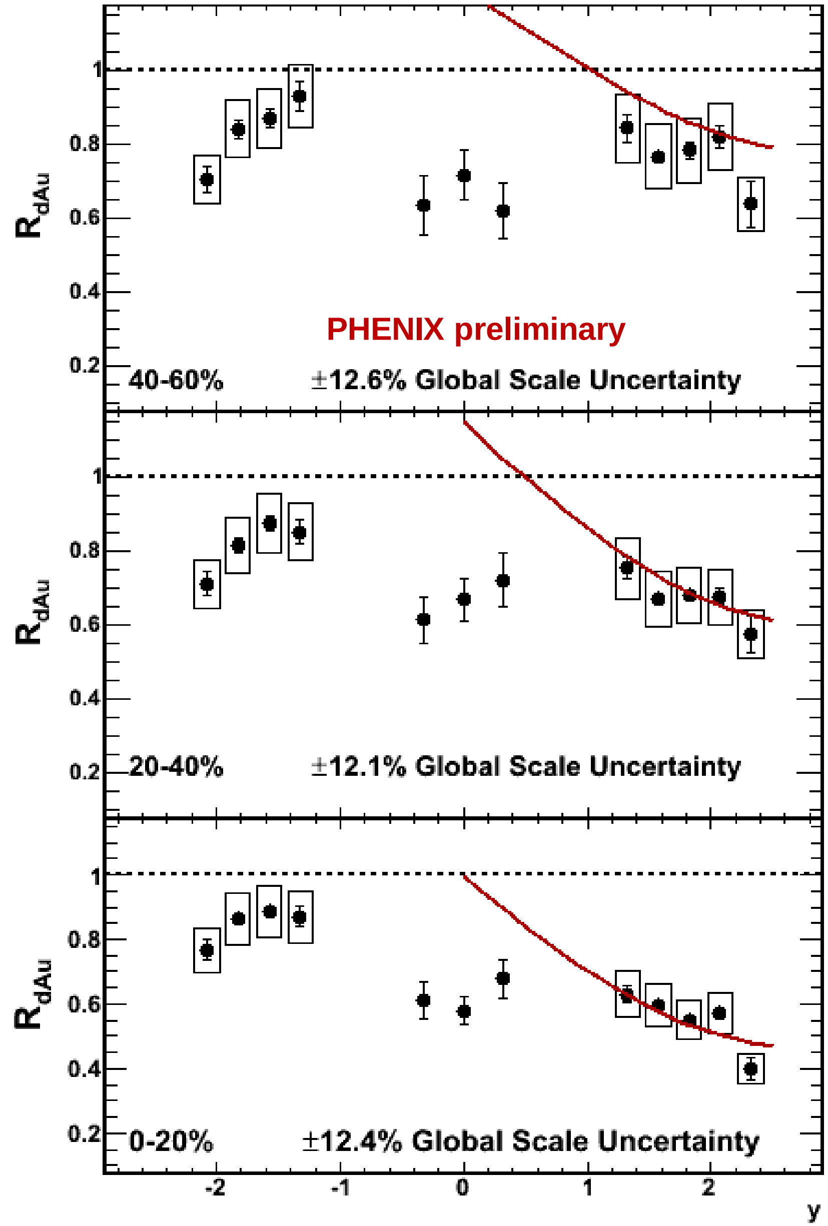
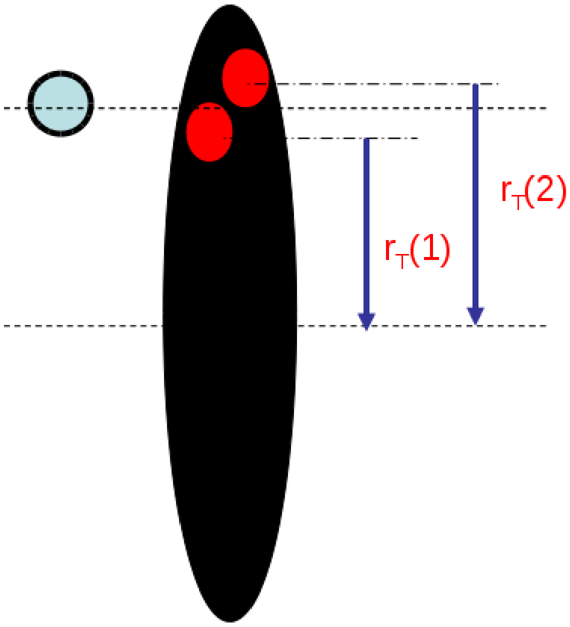


Centrality dependence of CNM effects (1)

arXiv:1010,1246 (2010)

Centrality dependence can be expressed as a function of the density weighted longitudinal thickness $\Lambda(r_T)$ seen by a deuteron nucleon as it passes through the Au nucleus at impact parameter r_T.



$$\Lambda(r_T) = \frac{1}{\rho_0} \int dz \rho(z, r_T)$$

One can assume several functional forms for the dependence of the J/psi suppression vs Λ(rt):

exponential: $M(r_T) = e^{-a\Lambda(r_T)}$

linear: $M(r_T) = 1 - a\Lambda(r_T)$

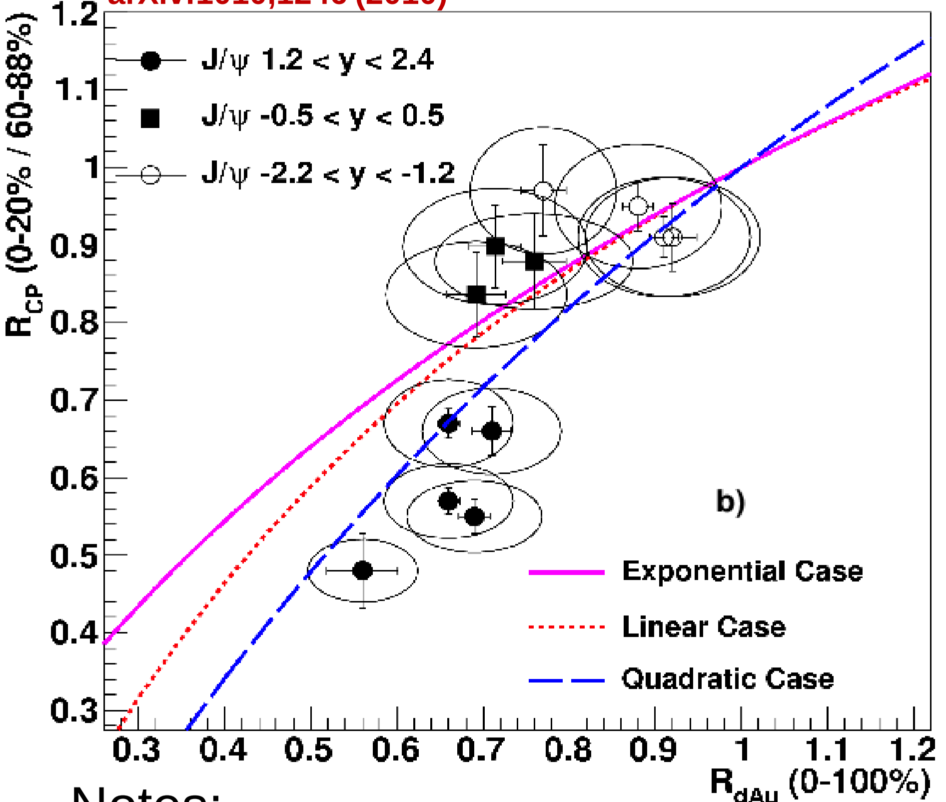
quadratic: $M(r_T) = 1 - a\Lambda(r_T)^2$

Knowing the distribution of r_T (vs centrality), each form induces a unique (parameter free) relationship between R_{CP} and R_{dA} (in arbitrary centrality bins)

One can plot these relationships, and compare to data (as well as models)

Centrality dependence of CNM effects (2)

arXiv:1010,1246 (2010)



Various thickness dependencies chosen for illustration differ mostly at forward rapidity.

Mid and backward rapidity points favor exponential or linear dependency.

Forward rapidity data show a different behavior, possibly pointing to different mechanism at play.

Notes:
- centrality dependent prediction in EPS09 assumes linear dependency
- break-up cross-section accounting assumes exponential dependency
- extrapolation from pA/dA to AA have always assumed linear dependency

None of the above works at forward rapidity (but we use it nonetheless)

d+Au summary

Two approaches emerge for describing Cold Nuclear Matter effects on J/ψ production in d+Au collisions:

- **(poorly constrained) npdf + initial energy loss + $\sigma_{breakup}$**
  it cannot describe latest PHENIX data at forward rapidity. Additional effects might be at play.

- **gluon saturation CGC**
  It provides an alternative description of the collision at low x_2 (y>0) and (at least qualitative) explanations to some of the observed effects.

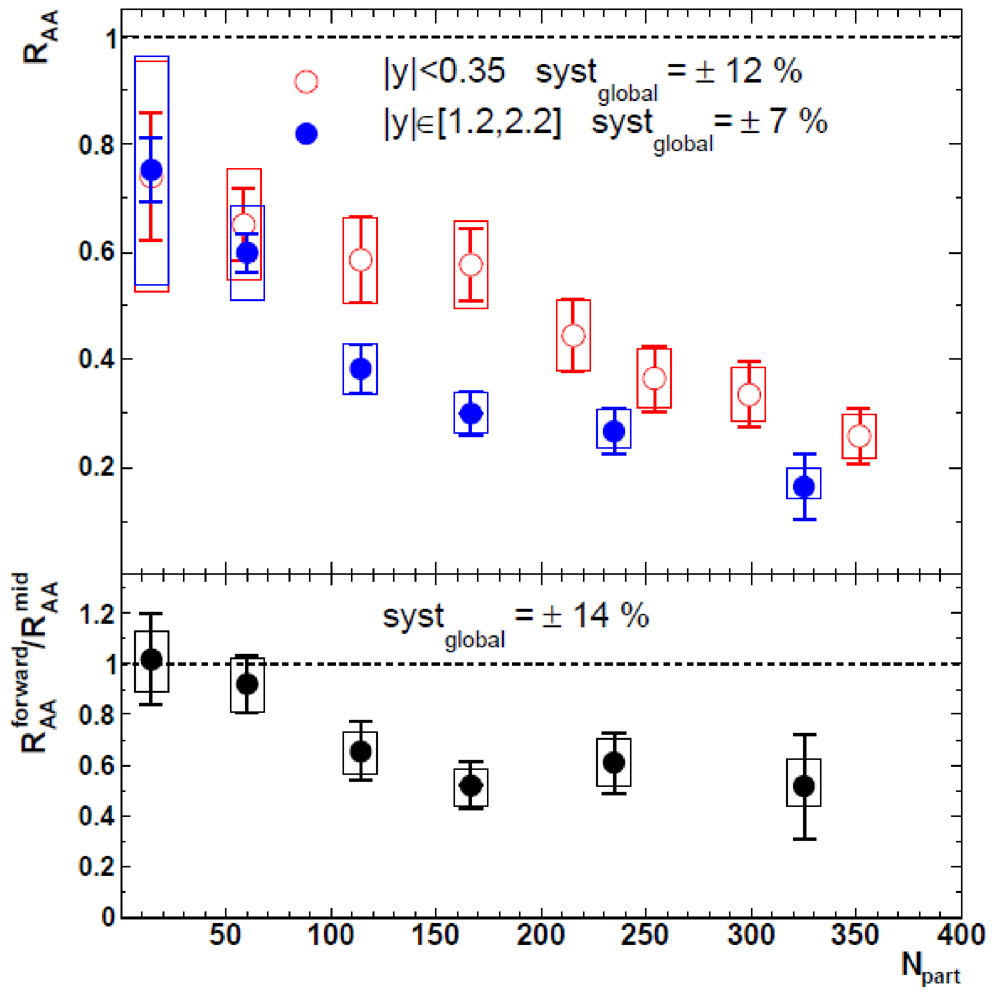
  hovever, it has no prediction for high x ($y\leq0$).

  - How does CGC connect to the more standard approach above ?
  - How does one extrapolate CGC from d+A to A+A ?

III. A+A collisions: anomalous suppression ?

J/ψ R_{AA} vs N_{part}

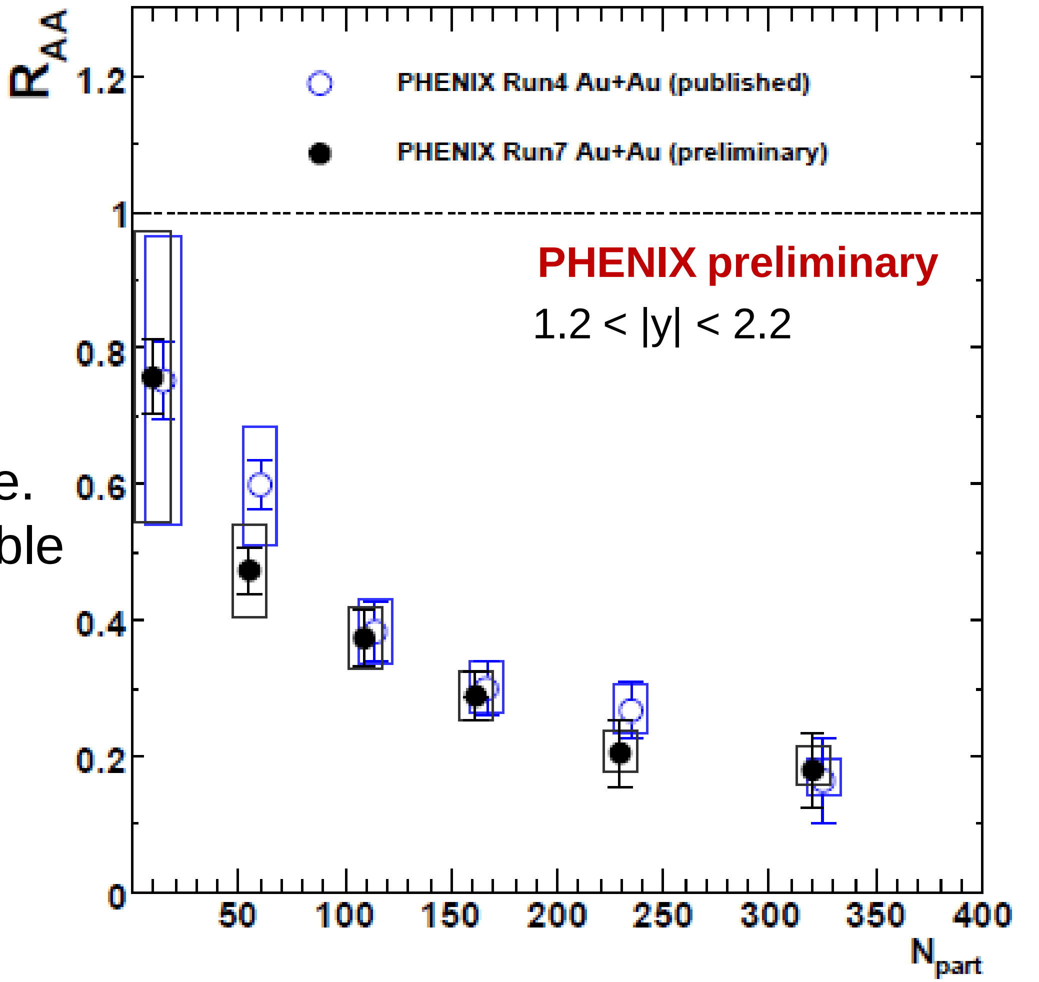
2004 data published in
PRL 98, 232301 (2007)
J/ψ R_{AA} vs N_{part}, p_T and rapidity



J/ψ R_{AA} vs N_{part}

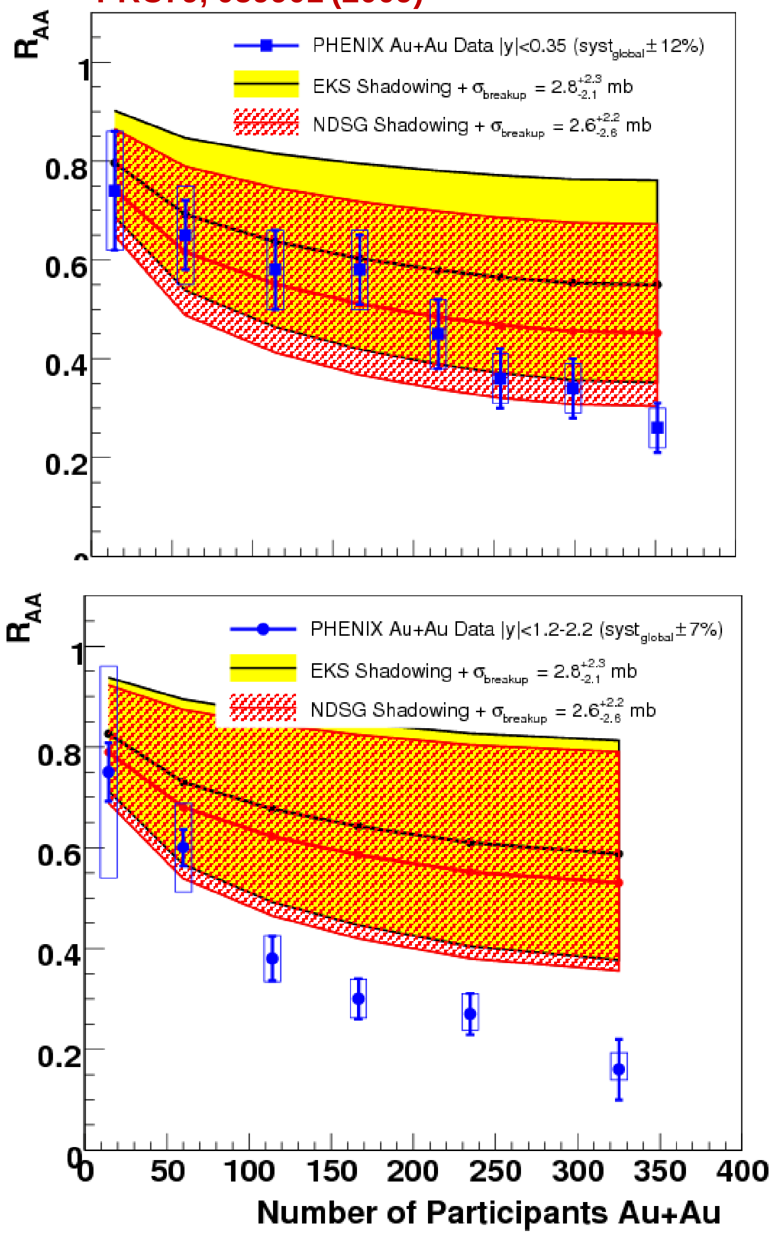
2004 data published in
PRL 98, 232301 (2007)
J/ψ R_{AA} vs N_{part}, p_T and rapidity

2007 data (~ x4 statistics) are still being analyzed.
Preliminary R_{AA} (and v_2) is available.
Final results should become available soon.



J/ψ R_{AA} and extrapolated CNM (1)

PRC79, 059901 (2009)



Here a unique break-up cross section is derived from the mid and forward rapidity d+Au data (2003), for two npdf prescriptions, and extrapolated to Au+Au

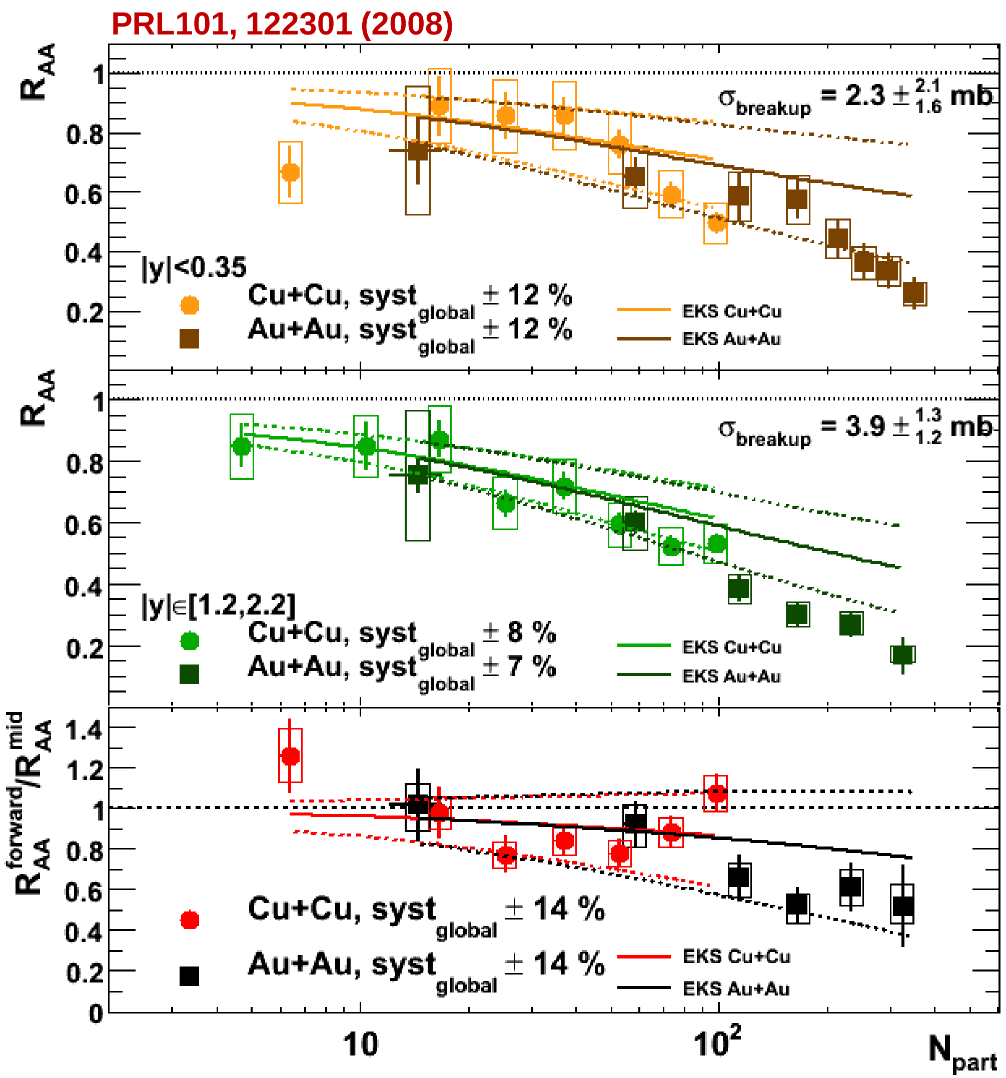
Error bars from CNM are large;

Difference between npdf prescriptions is modest;

Even in the worst case, there is some additional suppression observed in most central Au+Au collisions, beyond CNM;

There **appear to** be more anomalous suppression at forward rapidity.

J/ψ R_{AA} and extrapolated CNM (2)



Data are from 2005 Cu-Cu and 2004 Au-Au.

Lines are cold nuclear matter effects extrapolated from 2003 d-Au data, using different $\sigma_{breakup}$ for mid and forward rapidity

Cu-Cu and Au-Au ratios match well where they overlap.
In Au+Au the suppression is larger than expected from CNM

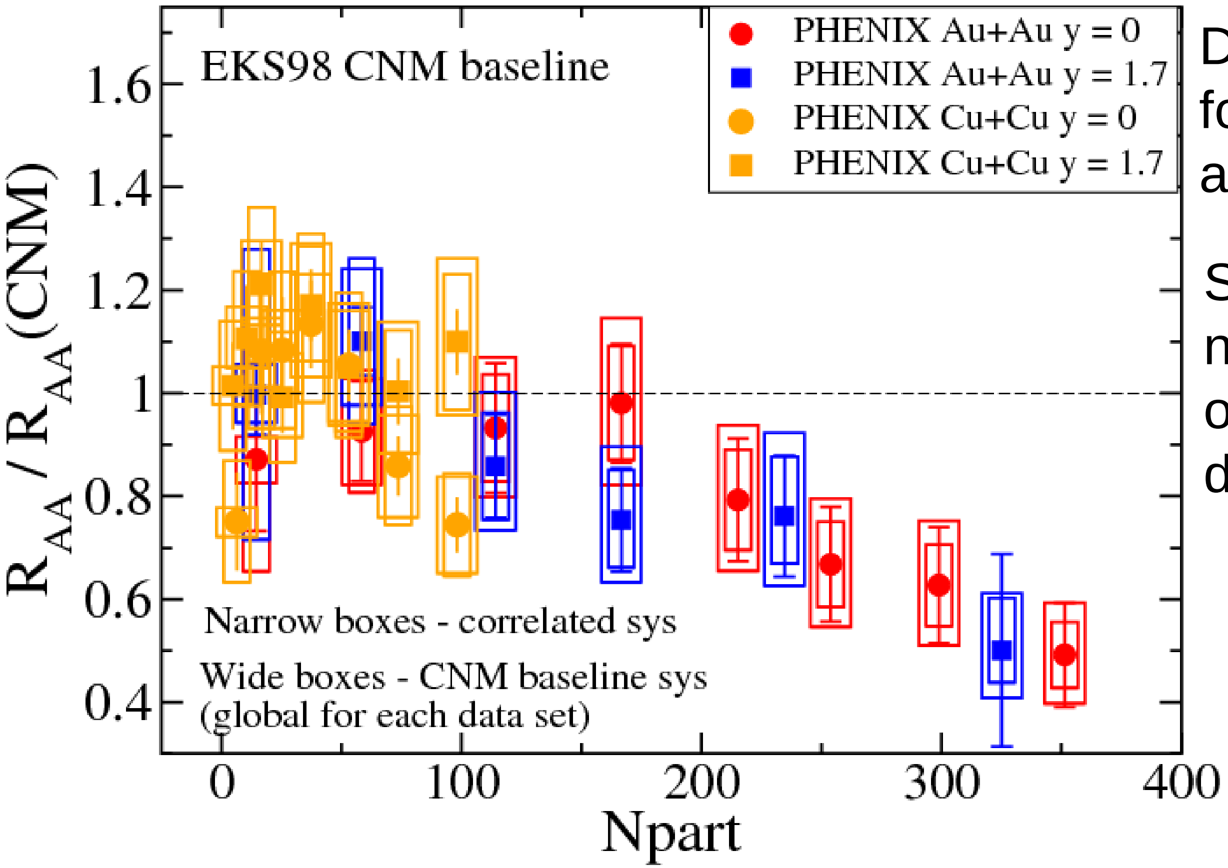
There is (still) more suppression at forward rapidity than at mid-rapidity, but the difference can be absorbed by CNM

J/ψ R_{AA} over CNM in Cu+Cu and Au+Au

R_{AA}/R_{AA}(CNM) vs N_{part}

Calculations from A. Frawley (INT workshop, 2009)

$\sigma_{breakup}$ and errors estimated from 2008 data

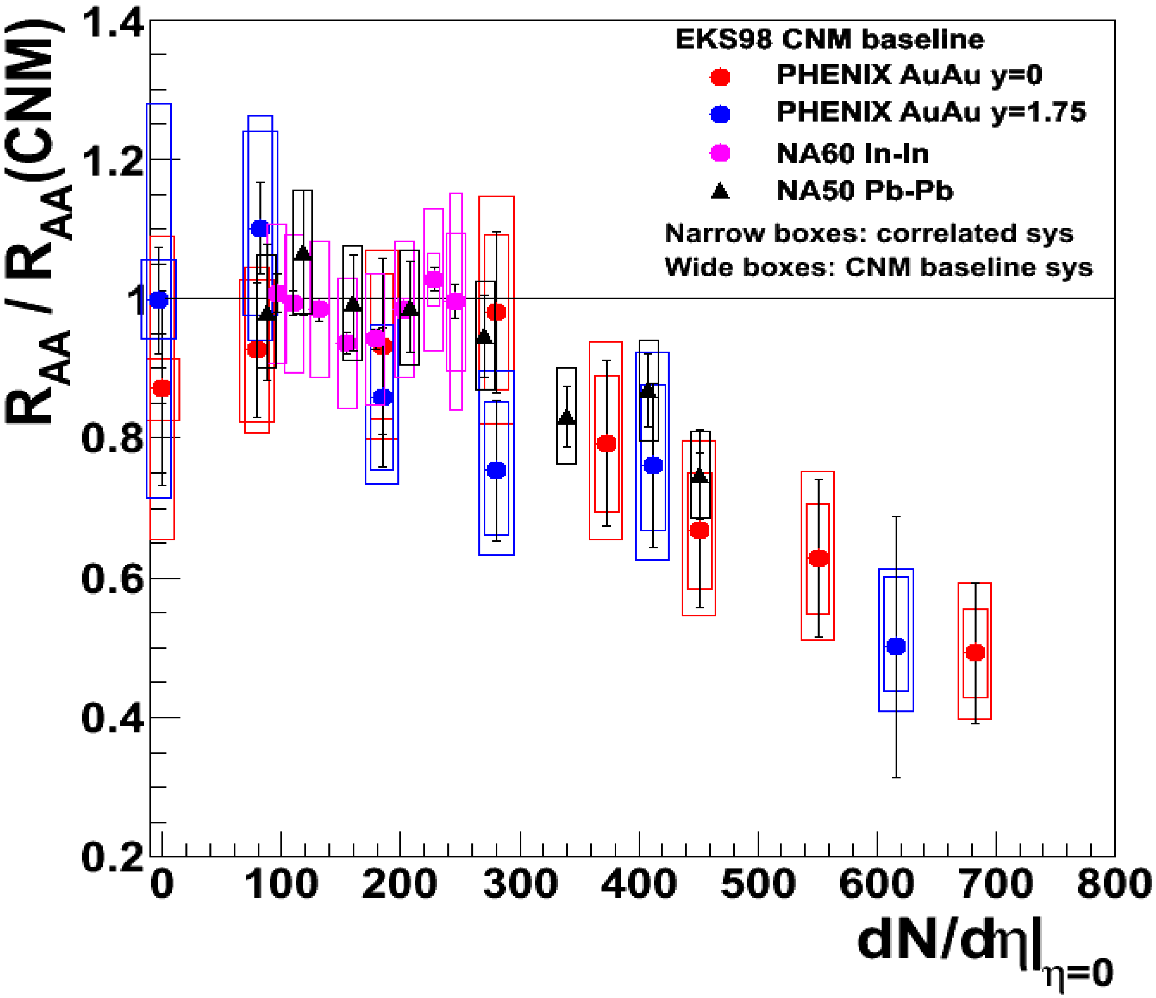


Differences between mid and forward rapidity measurement are washed out.

Suppression beyond cold nuclear matter effects is observed, consistent with deconfinement

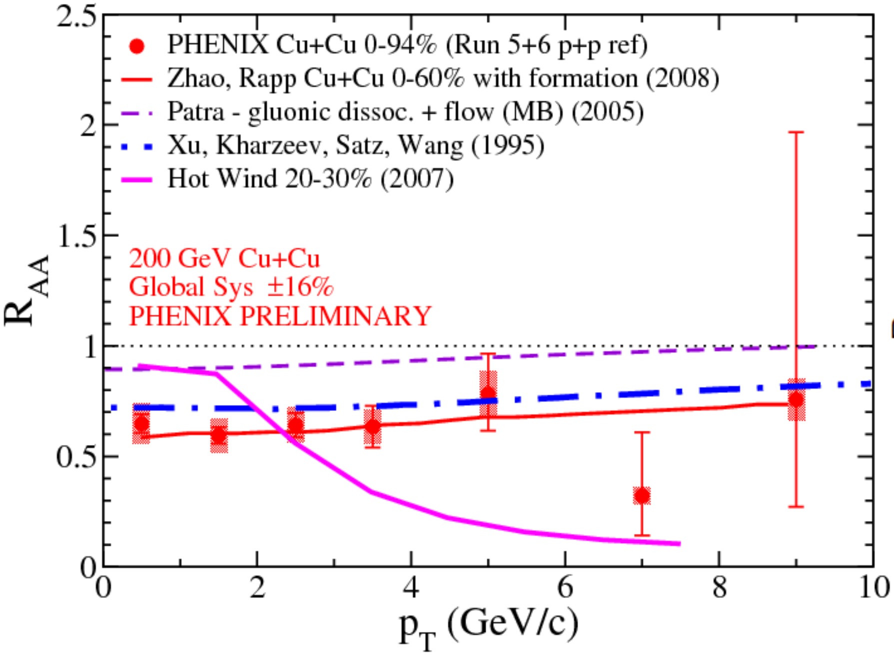
Comparison to SPS data

$R_{AA}/R_{AA}(\text{CNM})$ vs $dN/d\eta$ (at $\eta=0$)

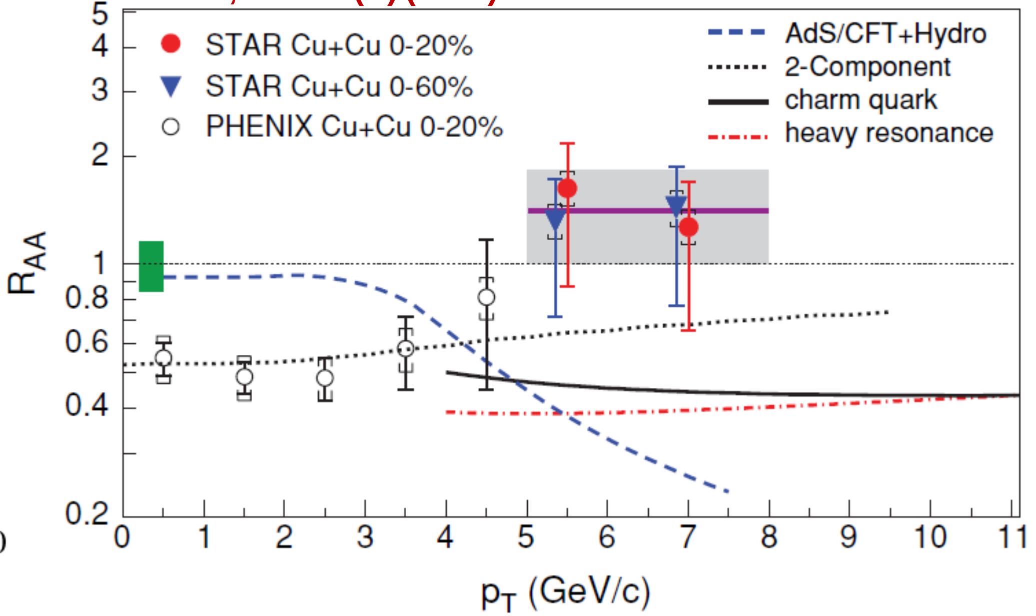


Here the *anomalous* J/ψ suppression is compared between SPS and RHIC, as a function of the number of charged particles at mid-rapidity.

p_T dependency (1) Cu+Cu collision



PRC80, 041902(R) (2009)



Left is minimum bias Cu+Cu collisions
Right is 0-20% central Cu+Cu collisions, adding STAR high p_T data (red points)
Possible increase of R_{CuCu} observed at hight p_T

Behavior at high p_T is very discriminating vs models,
but we need much more statistics to draw firm conclusions

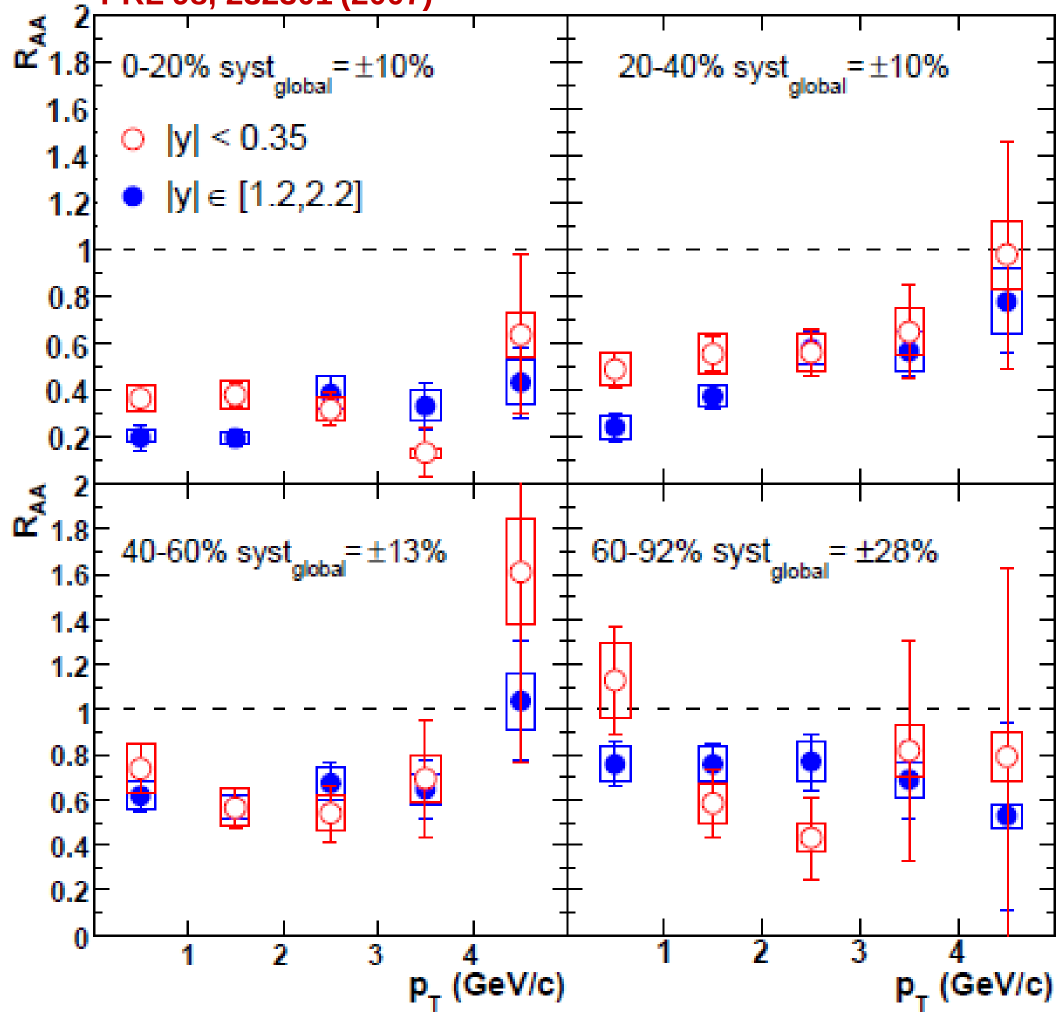
p_T dependency (2) Au+Au collisions

Some hint of increase with p_T for central collisions, but:

- errors are large
- p_T coverage is quite modest.

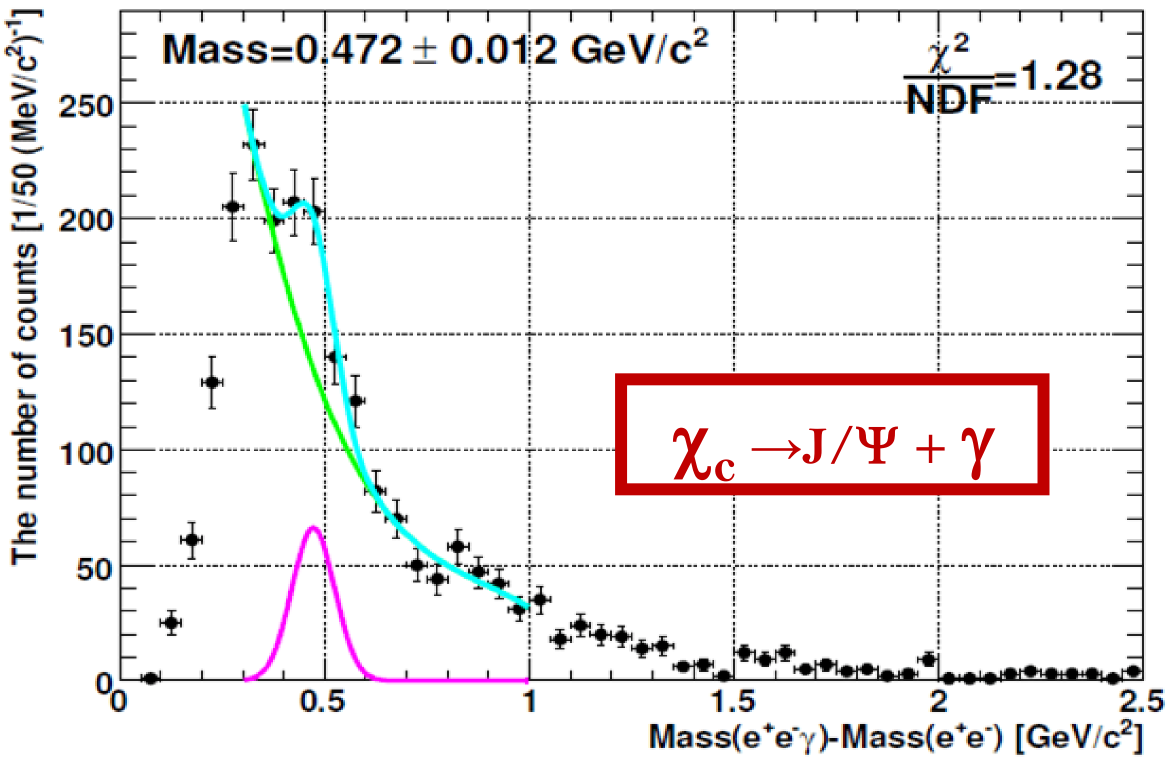
Note that an increase of R_{AA} at high p_T is consistent with an increase of $<p_T^2>$ from p+p to A+A (Cronin effect ?)

PRL 98, 232301 (2007)



IV. More tools: other resonances

χ_c production



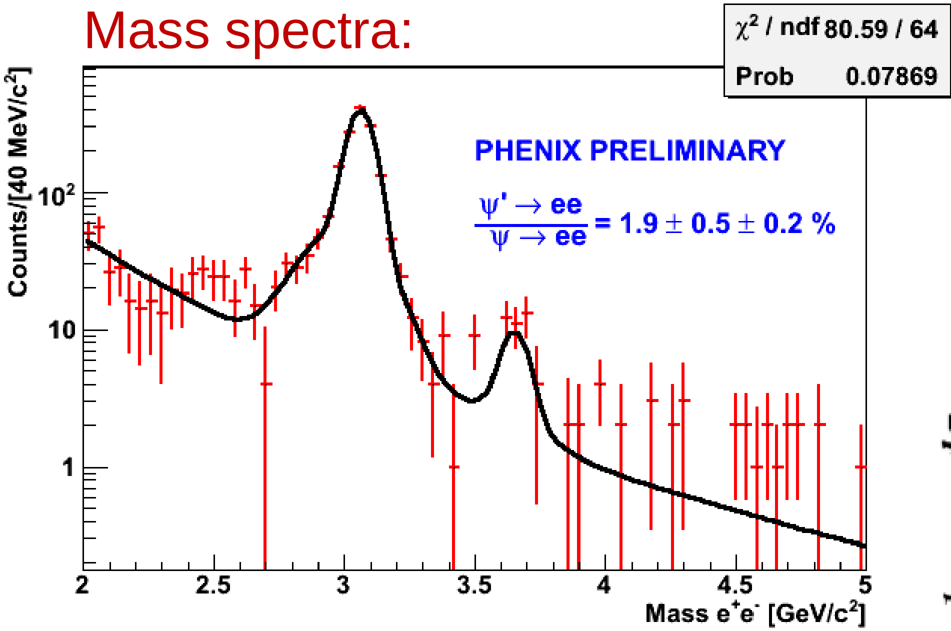
Measured at mid rapidity via di-electron + photon in EMCal
Provides: feed-down contribution to J/ψ

J/ψ from χ_c < 42% (90% CL)

PHENIX preliminary

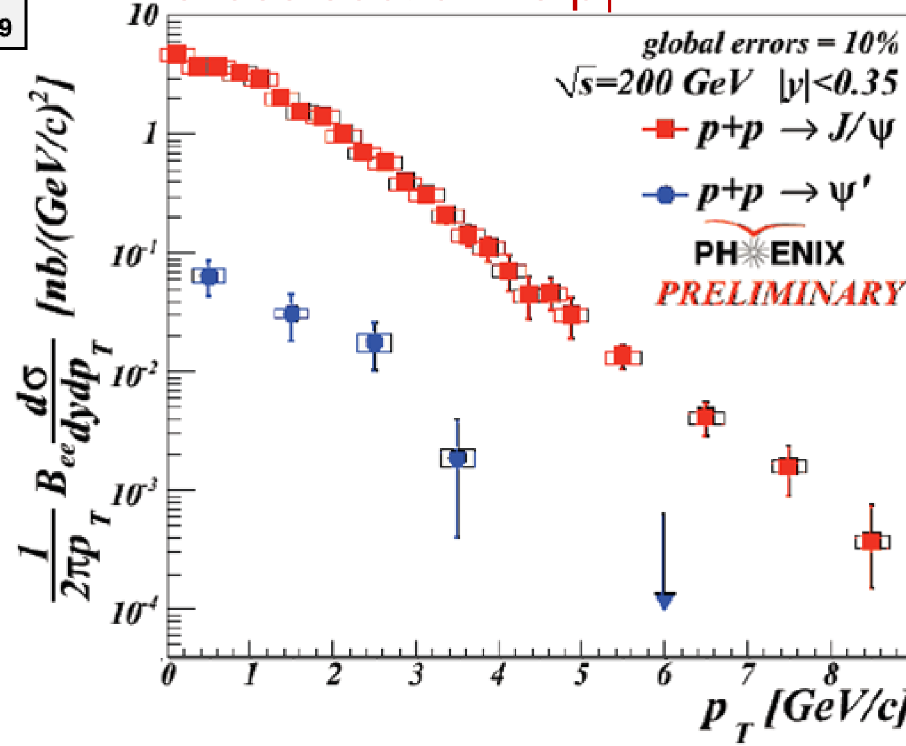
ψ' production

Mass spectra:

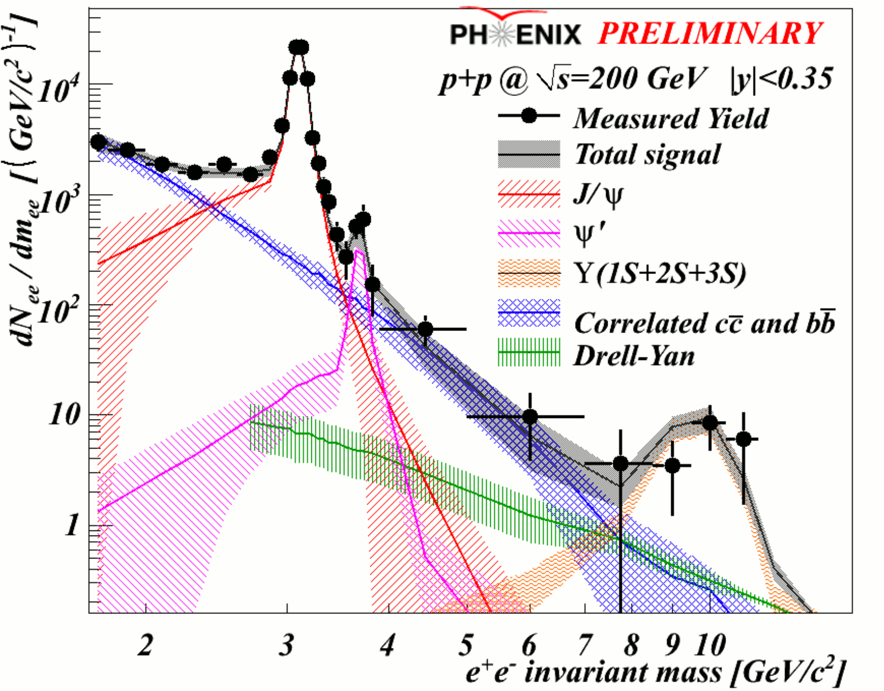


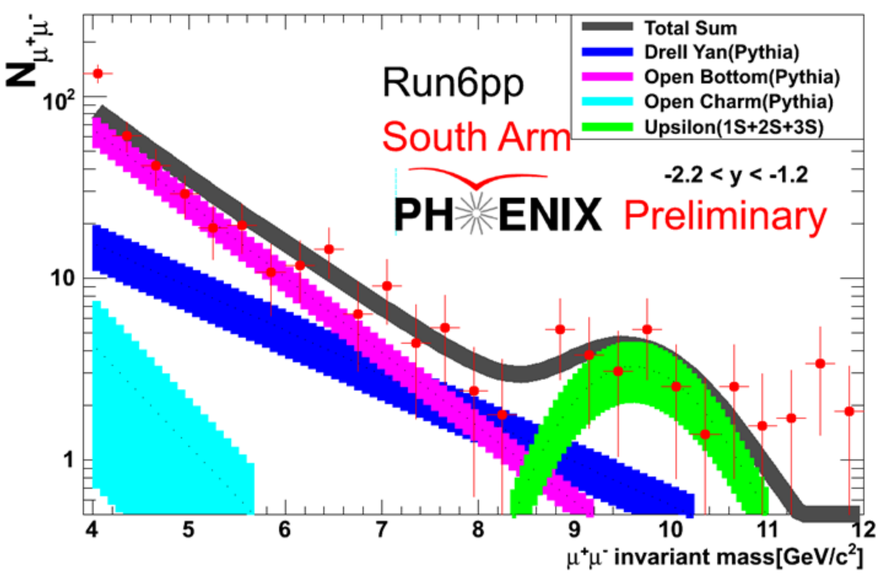
$\boxed{J/\psi \text{ from } \psi' = 8.6 \pm 2.5\ \%}$

Cross section vs p_T:

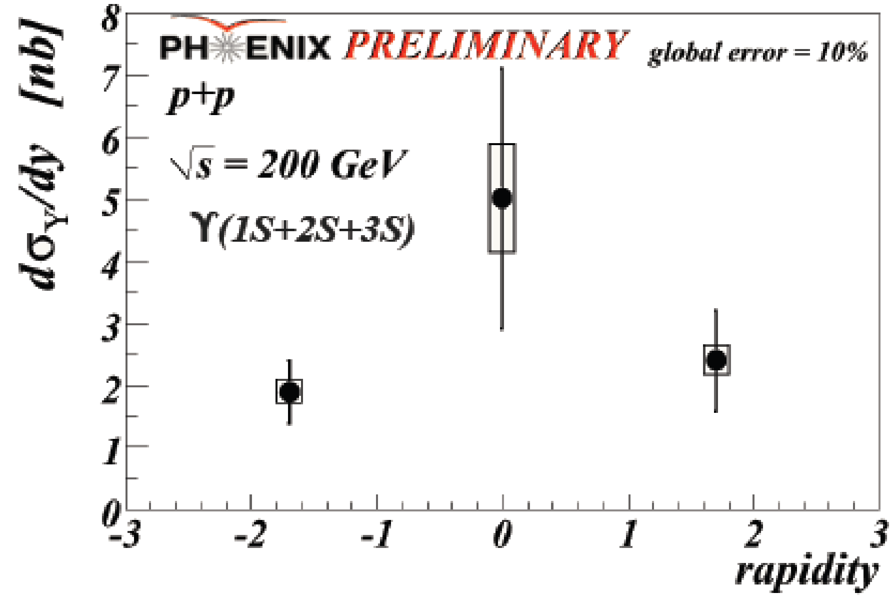


Υ production in p+p collisions





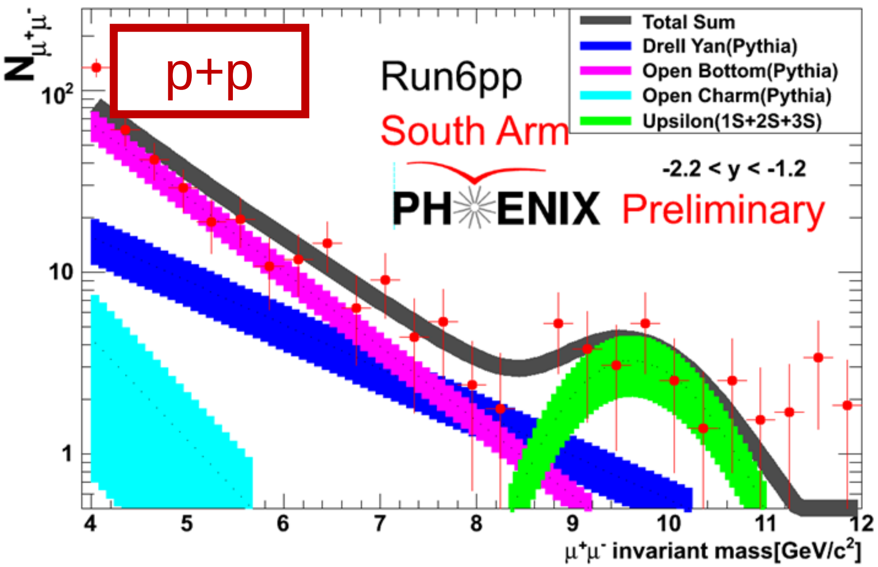
Rapidity dependence:

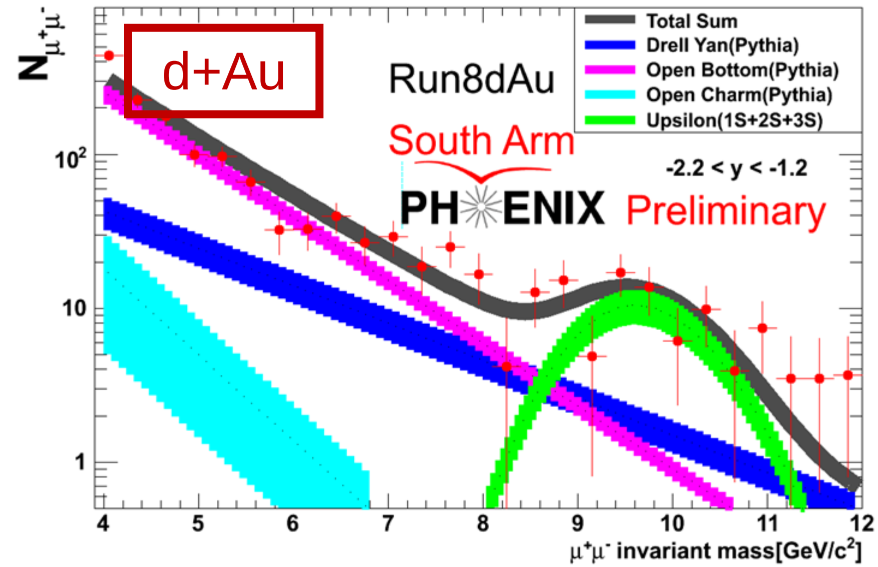


Cross section:

$$\boxed{BR * \frac{d\sigma}{dy}\Big|_{|y|<0.35} = 114^{+46}_{-45}\, pb}$$

Υ R_{dAu}

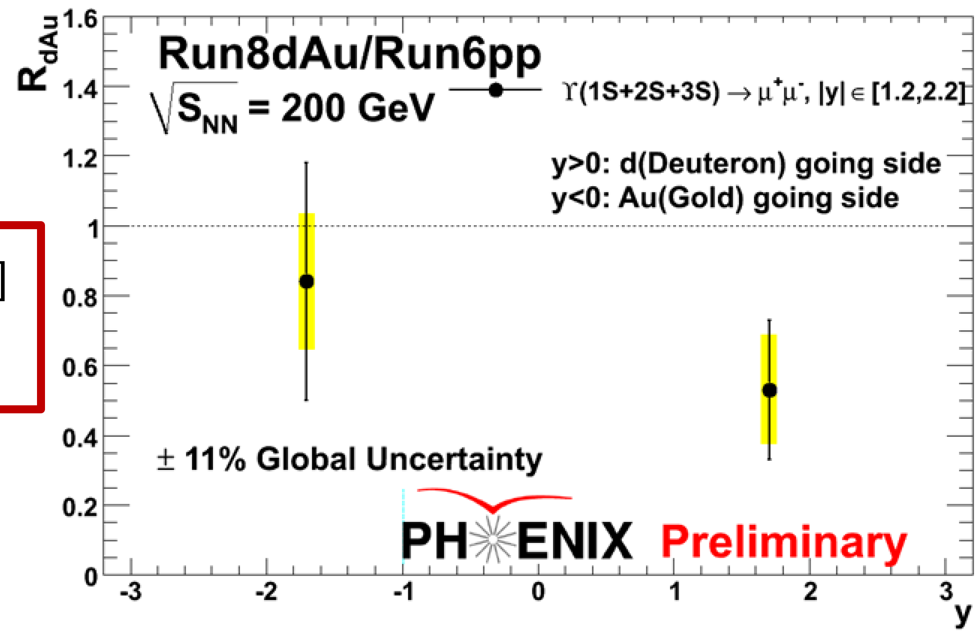




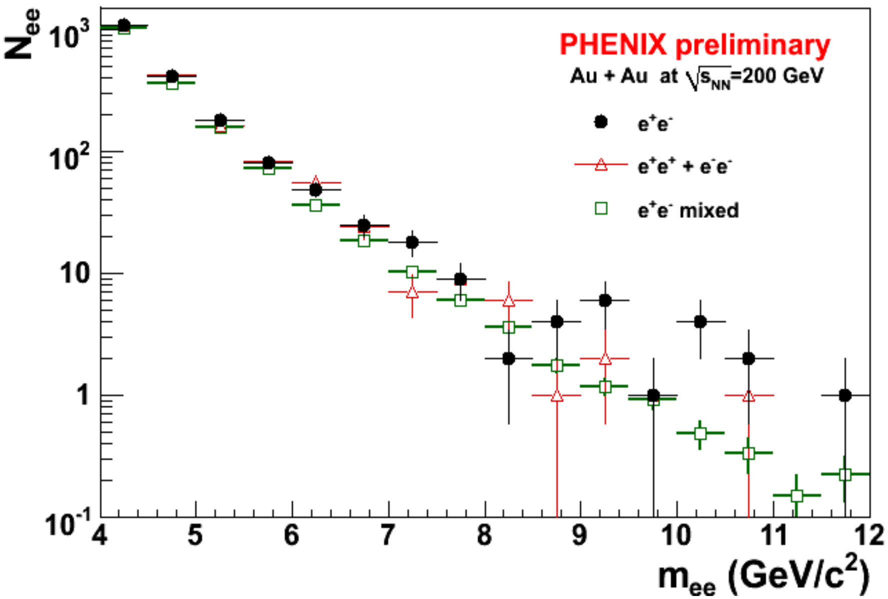
First Υ measurement at forward rapidity (1.2<|y|<2.2) in d+Au collisions

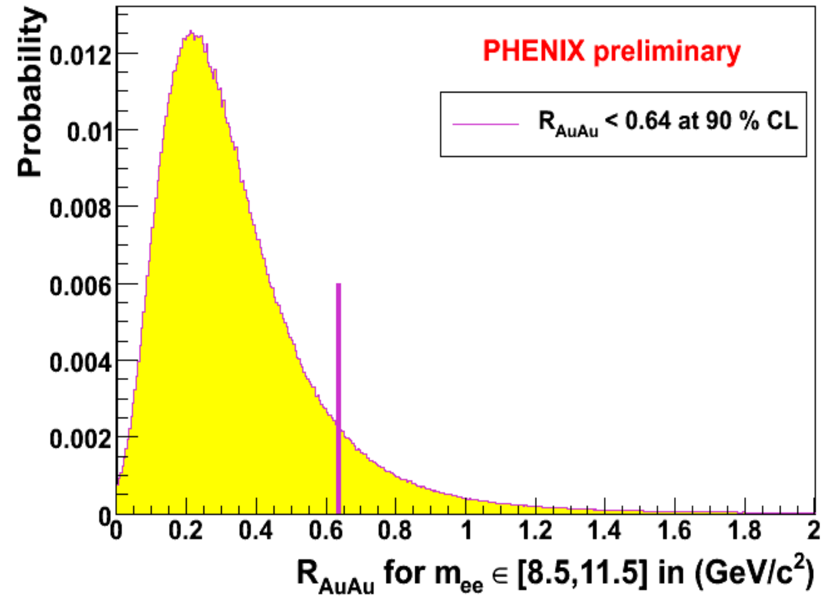
R_{dAu} = 0.84±0.34(stat.)±0.20(sys.), y [-2.2, -1.2]

R_{dAu} = 0.53±0.20(stat.)±0.16(sys.), y [1.2, 2.2]



ϒ (or rather: high mass di-leptons) R_{AA}





- Compute a double ratio of (high mass dileptons)/(J/ψ) between p+p and Au+Au, to cancel systematics
- Using J/ψ R_{AA} , derive a 90% CL for high-mass dileptons R_{AA}

R_{AuAu} [8.5,11.5] < 0.64 at 90% C.L.

Conclusions

Understanding heavy quarkonia production in p+p collisions has shown a lot of activity recently, notably due to the availability of

- more precise J/ψ data
- other resonances

(not to mention J/ψ “polarization”, not discussed here)

Two approaches emerge for describing Cold Nuclear Matter effects on J/ψ production in d+Au collisions:

- (poorly constrained) npdf + initial energy loss + $\sigma_{breakup}$
- gluon saturation CGC (at low x)

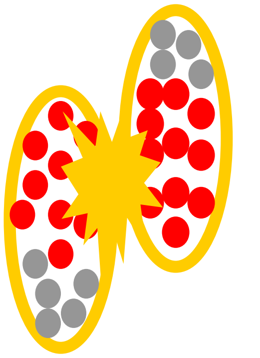
Note that the interplay between the two is not clear (to me)

It is critical to understand *all* these CNM effects, and how they extrapolate to Au+Au, if one wants to be quantitative about any *anomalous* suppression in Au+Au

Tools to study heavy ion collisions (1)

Collision characterization:

Centrality is related to the distance between the center of colliding nuclei (impact parameter b)

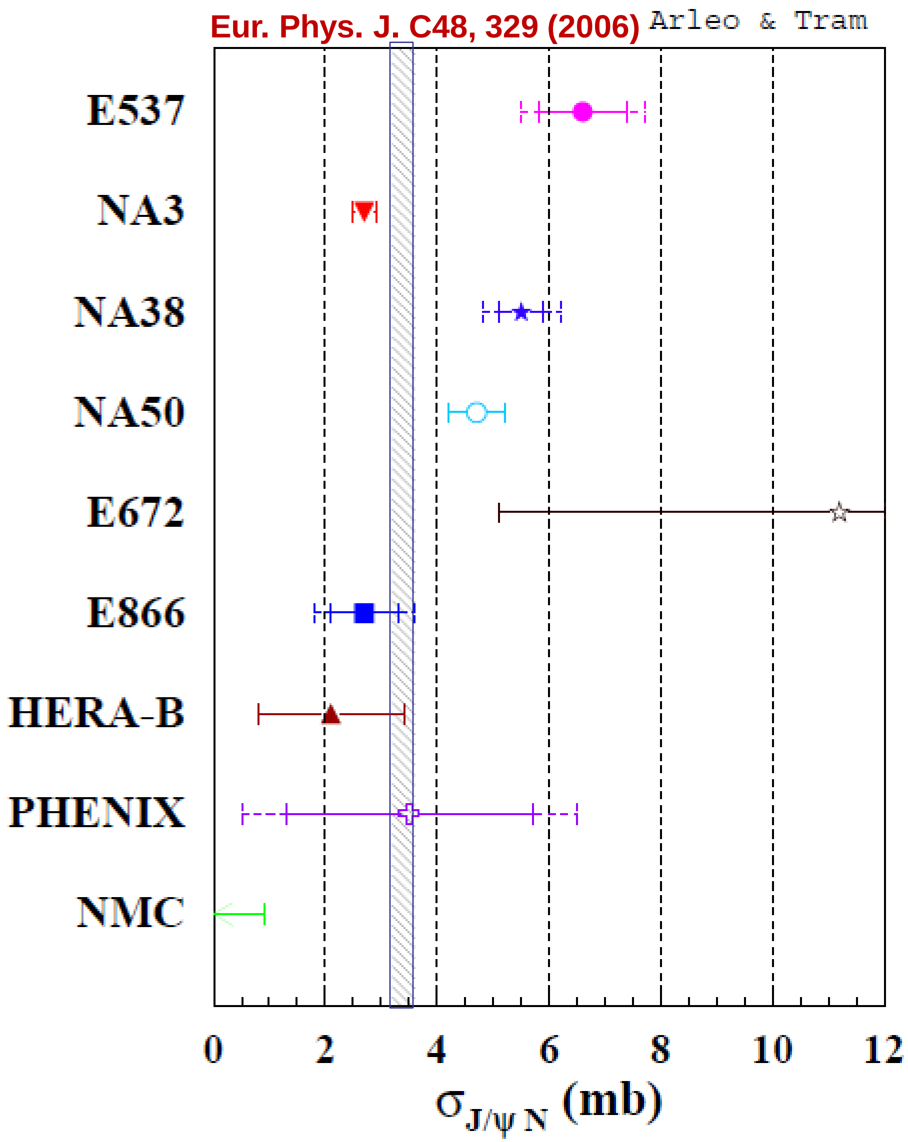


Central collisions: small b
Peripheral collisions: large b

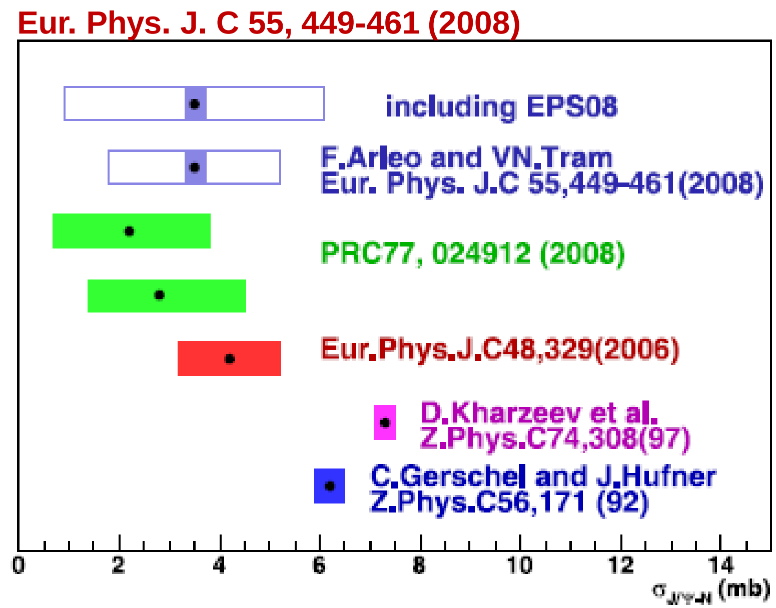
N_{part} is the number of nucleons participating to the HI collision
N_{coll} is the number of binary (pp) collisions in one HI collision
Both increase from peripheral to central collisions

Collision	N_{part}	N_{coll}
d+Au (all centralities)		7.6 ± 0.3
Au+Au (all centralities)	109 ± 4	258 ± 25
Au+Au (10% most central)	325 ± 3	955 ± 94

Energy dependence of $\sigma_{breakup}$ (2)



Several systematic studies of $\sigma_{breakup}$ (or $\sigma_{j/\psi N}$) are available, using all world data on J/ψ lepto and hadro- production



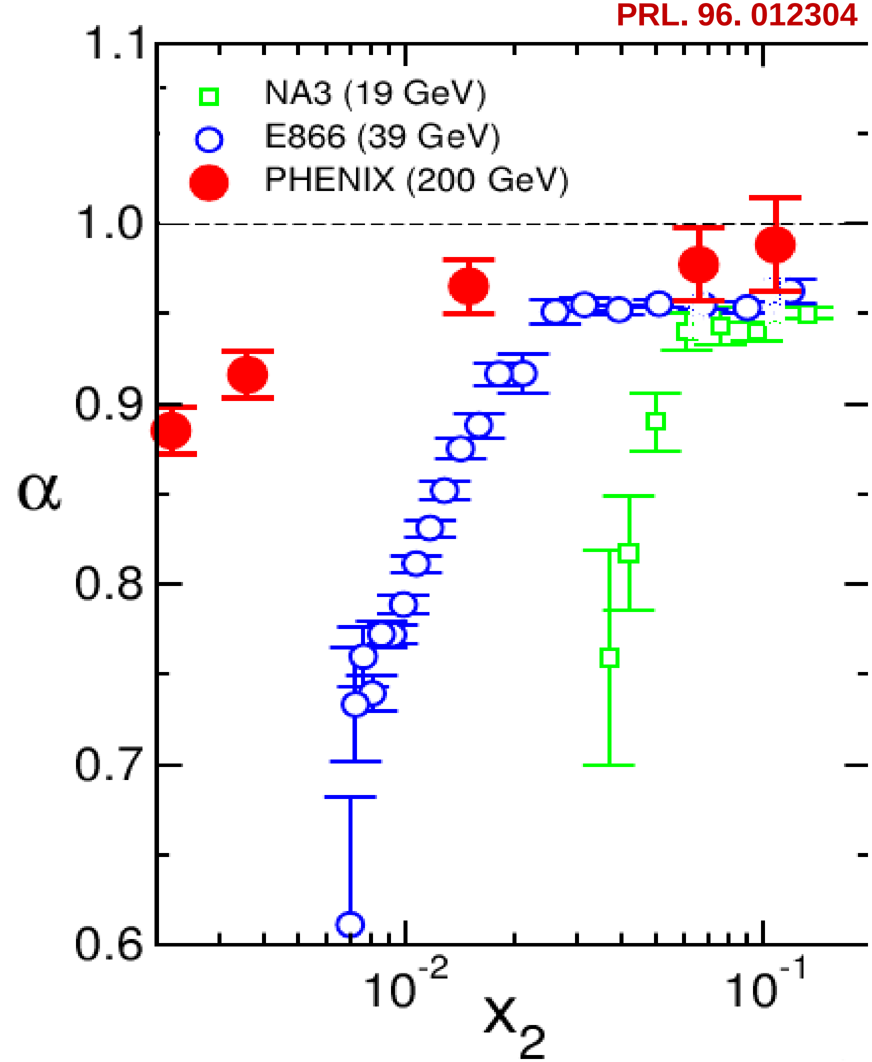
x_1, x_2, x_F dependency

Here use alpha instead of RdAu

$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$

npdf + $\sigma_{breakup}$ picture expects scaling as a function of x_2, which is obviously not observed.

PRL. 96. 012304



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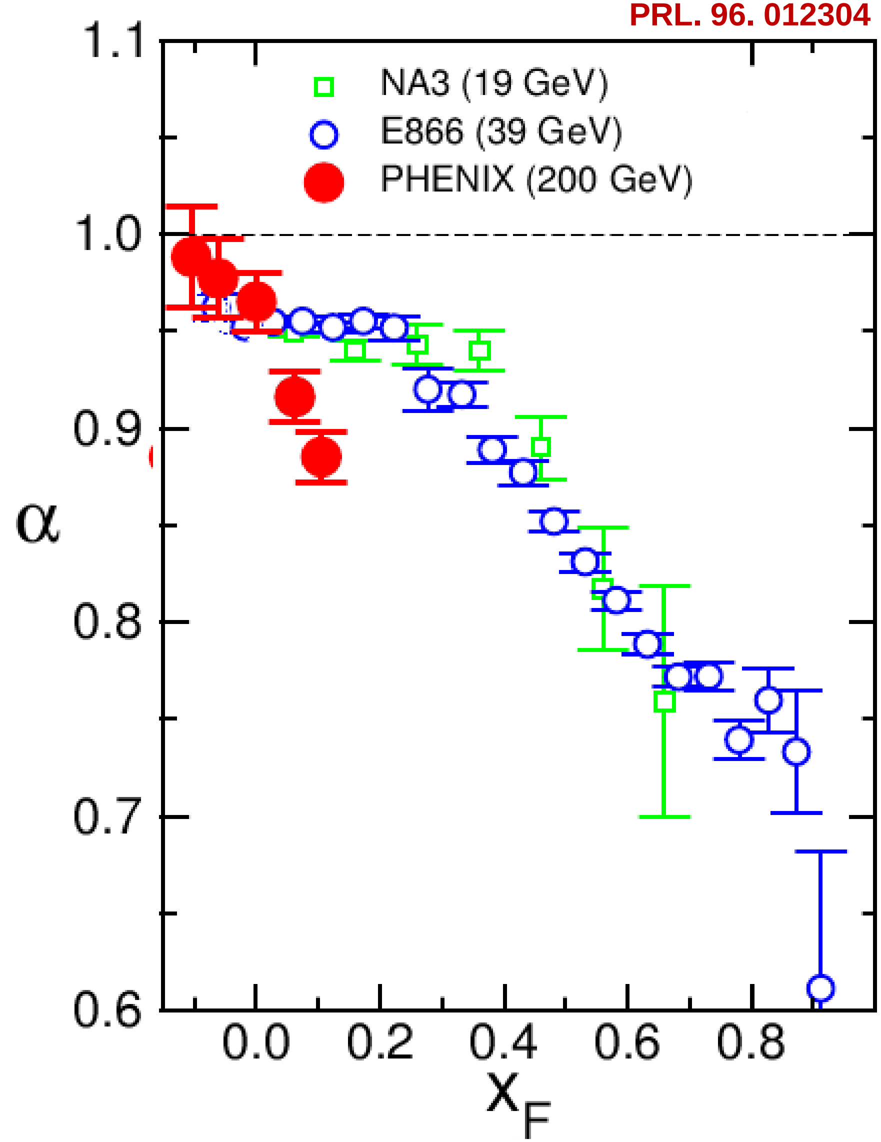
Somewhat better (though not perfect) scaling observed as a function of x_F.

PRL. 96. 012304



x_1, x_2, x_F dependency

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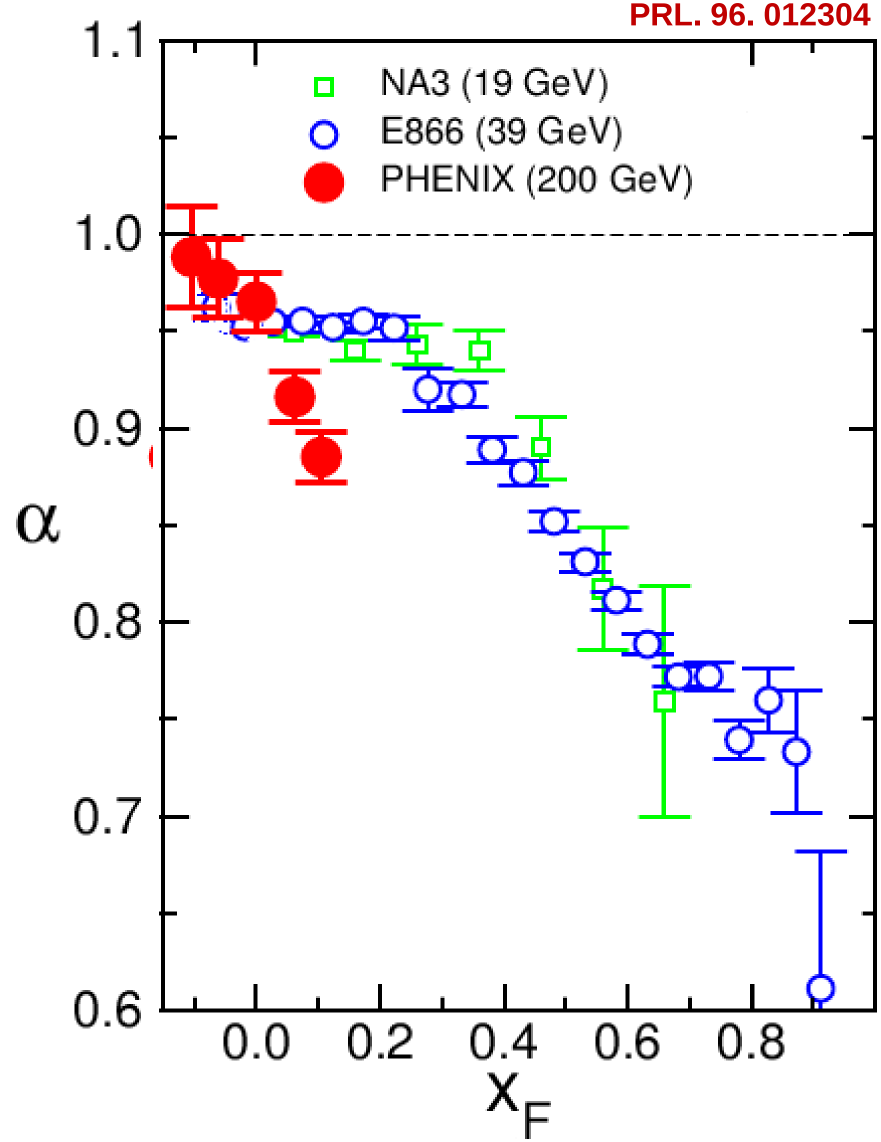
npdf + $\sigma_{breakup}$ picture expects scaling as a function of x_2, which is obviously not observed

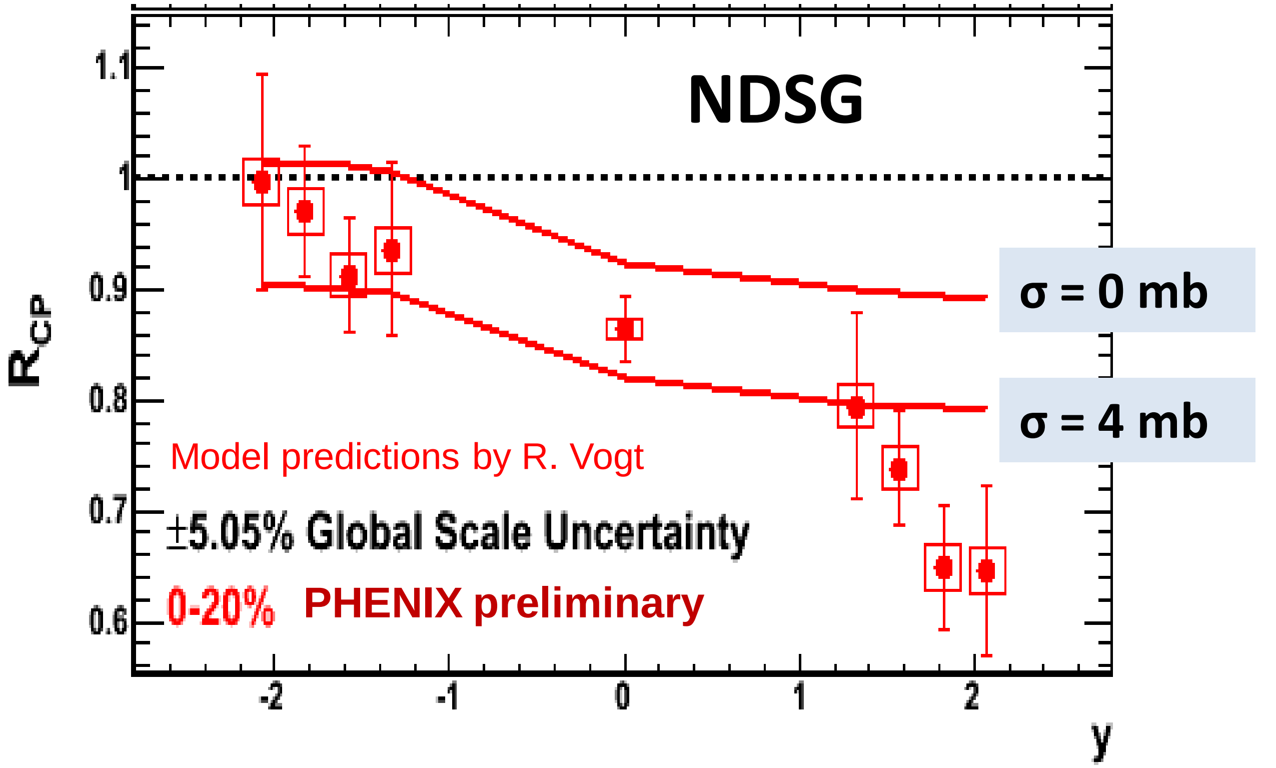
Somewhat better (though not perfect) scaling observed as a function of x_F.

At least for NA3 and E866, the high x_F decrease can be explained by initial state energy loss.

PRL. 96. 012304

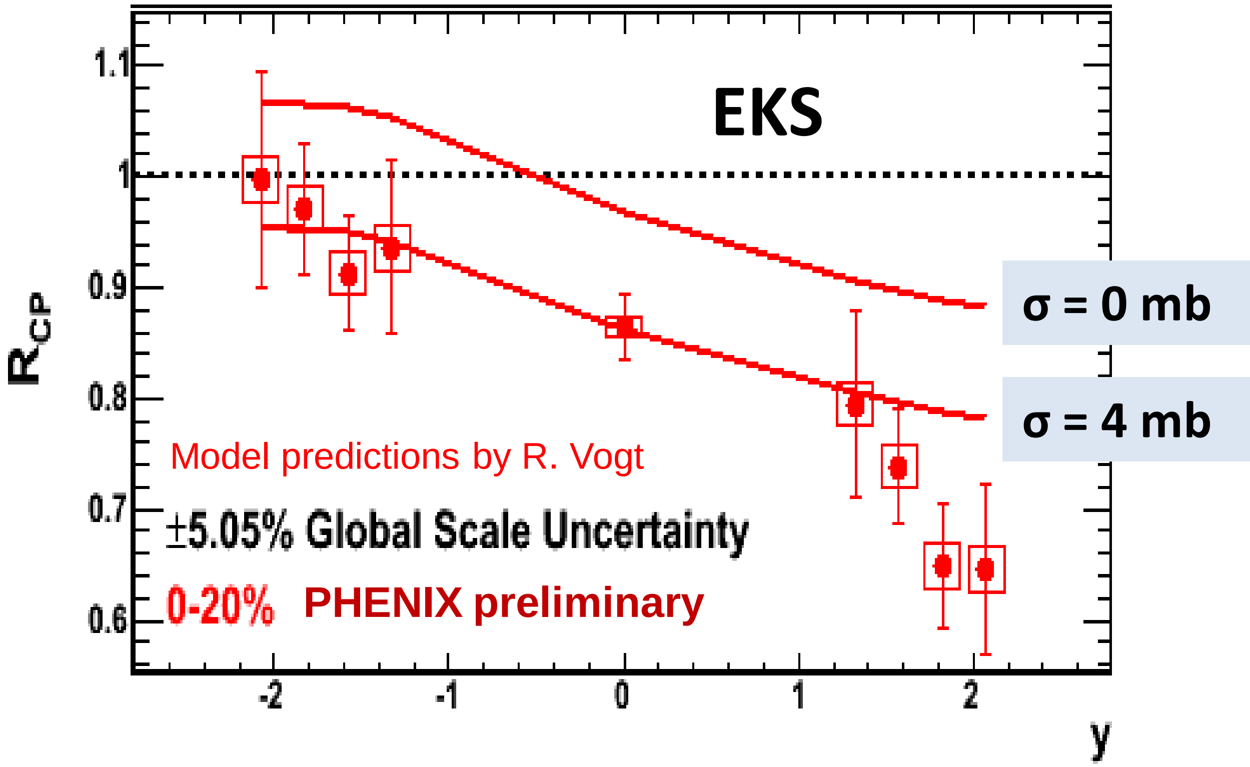


npdf + $\sigma_{breakup}$ vs data, using 2008 data set



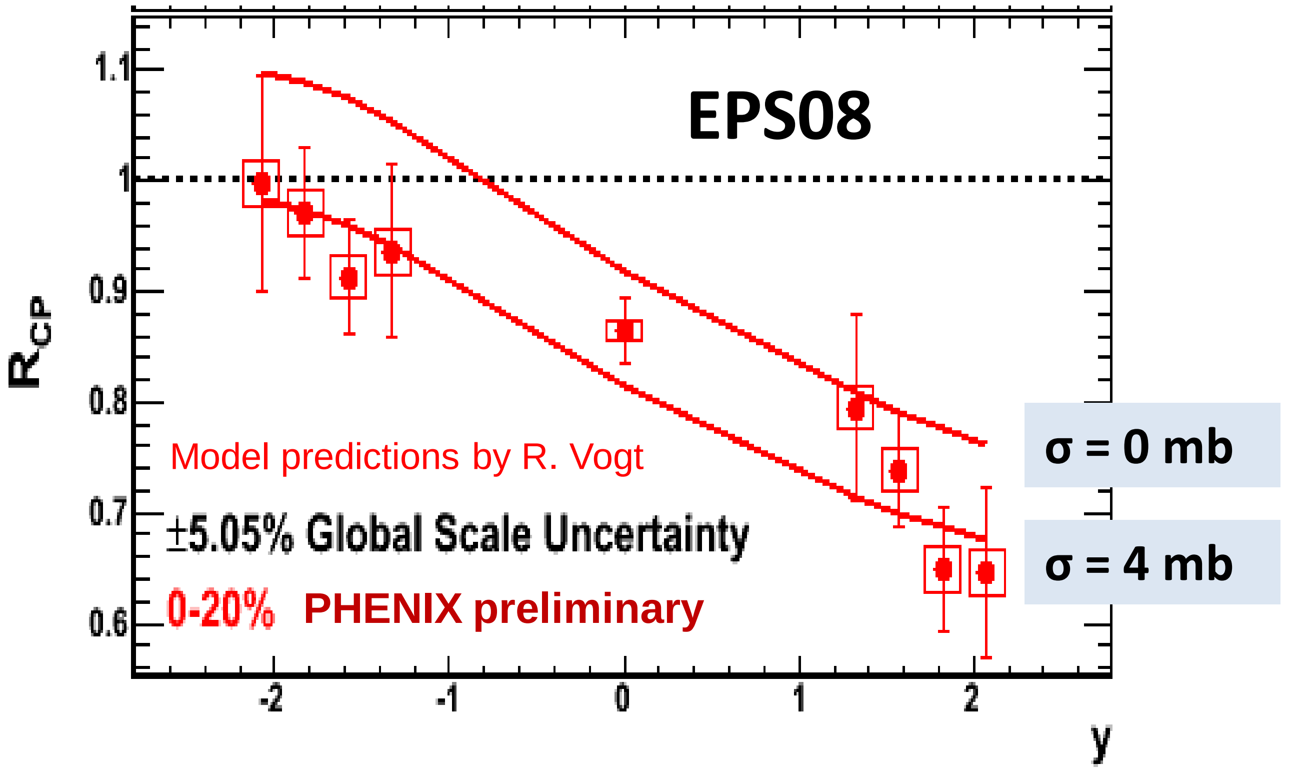
- Small and moderate shadowing fail to reproduce the high rapidity data

npdf + $\sigma_{breakup}$ vs data, using 2008 data set



- Small and moderate shadowing fail to reproduce the high rapidity data

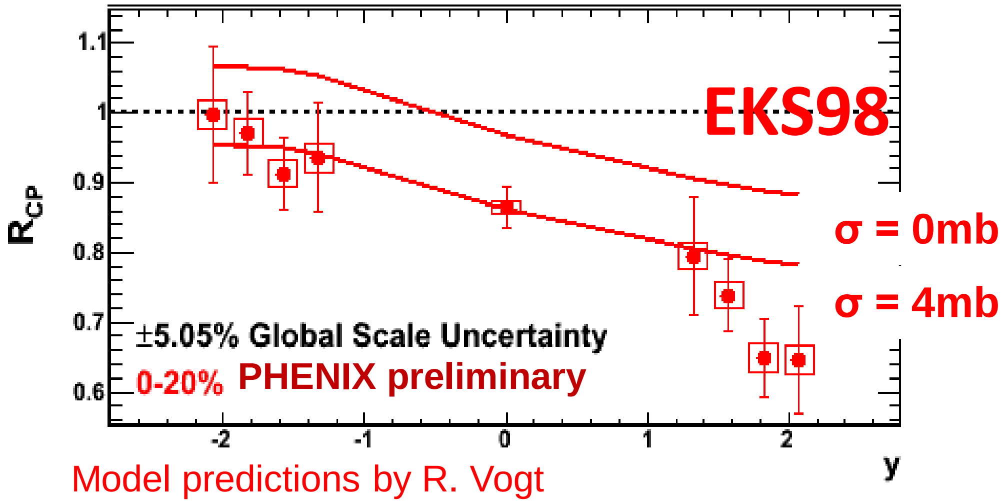
npdf + $\sigma_{breakup}$ vs data, using 2008 data set



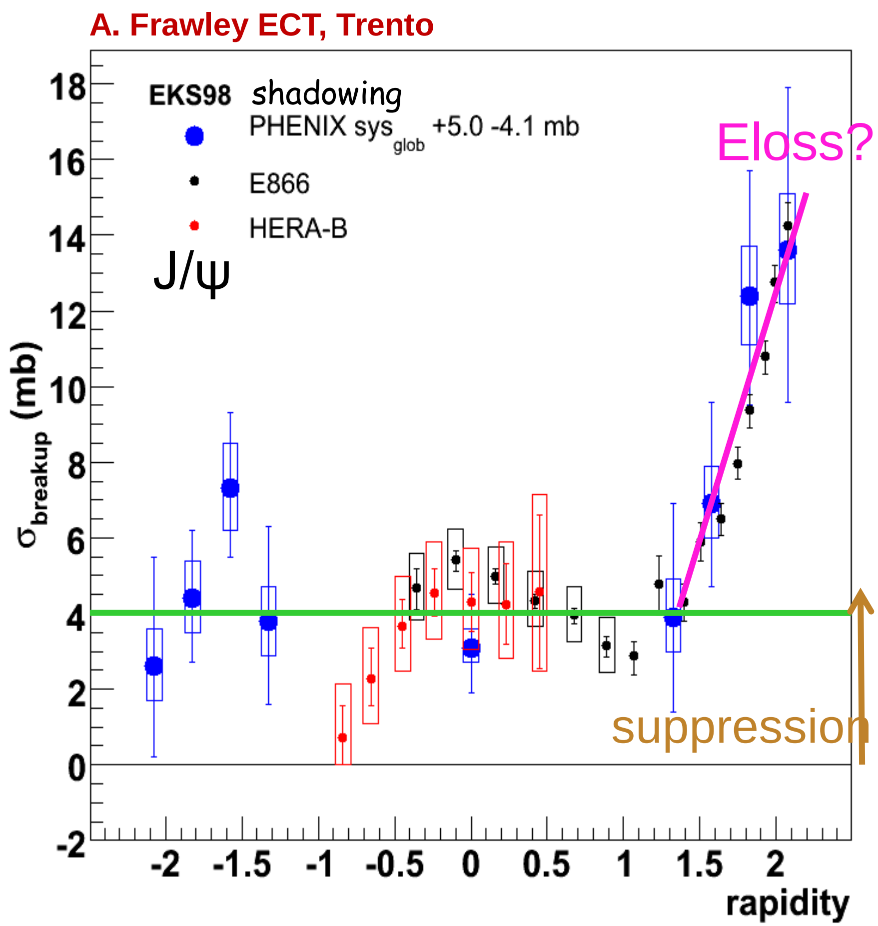
- Small and moderate shadowing fail to reproduce the high rapidity data
- Large shadowing (EPS08) does a better job, but does not really match lower energy data

Either we are missing some ingredient, or the full picture (npdf + $\sigma_{breakup}$) is not quite correct.

Effective $\sigma_{breakup}$ vs rapidity

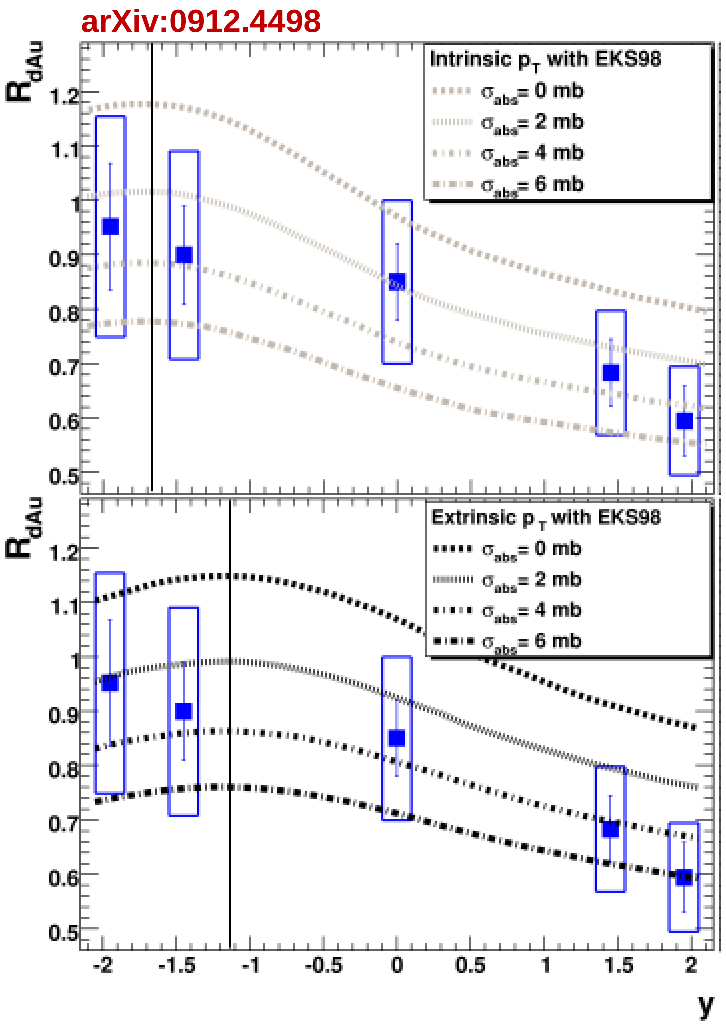


Model predictions by R. Vogt



- shadowing + fixed $\sigma_{breakup}$ don't match the observed rapidity dependency
- Use d+Au data to extract <u>effective</u> $\sigma_{breakup}$ as a function of rapidity which parameterizes all the effects that shadowing is missing
- Same trend is observed at mid and forward rapidity by E866 and HERA-B

Impact of production mechanism (1)



Statement from previous slide is even more true when properly accounting for the production kinematics :

How the p_T and y of the J/ψ relates to the initial partons' momentum (x_1 and x_2) depends on the production mechanism.

- for COM like processes, the reaction involved is of type 2→1 (*intrinsic* p_T)

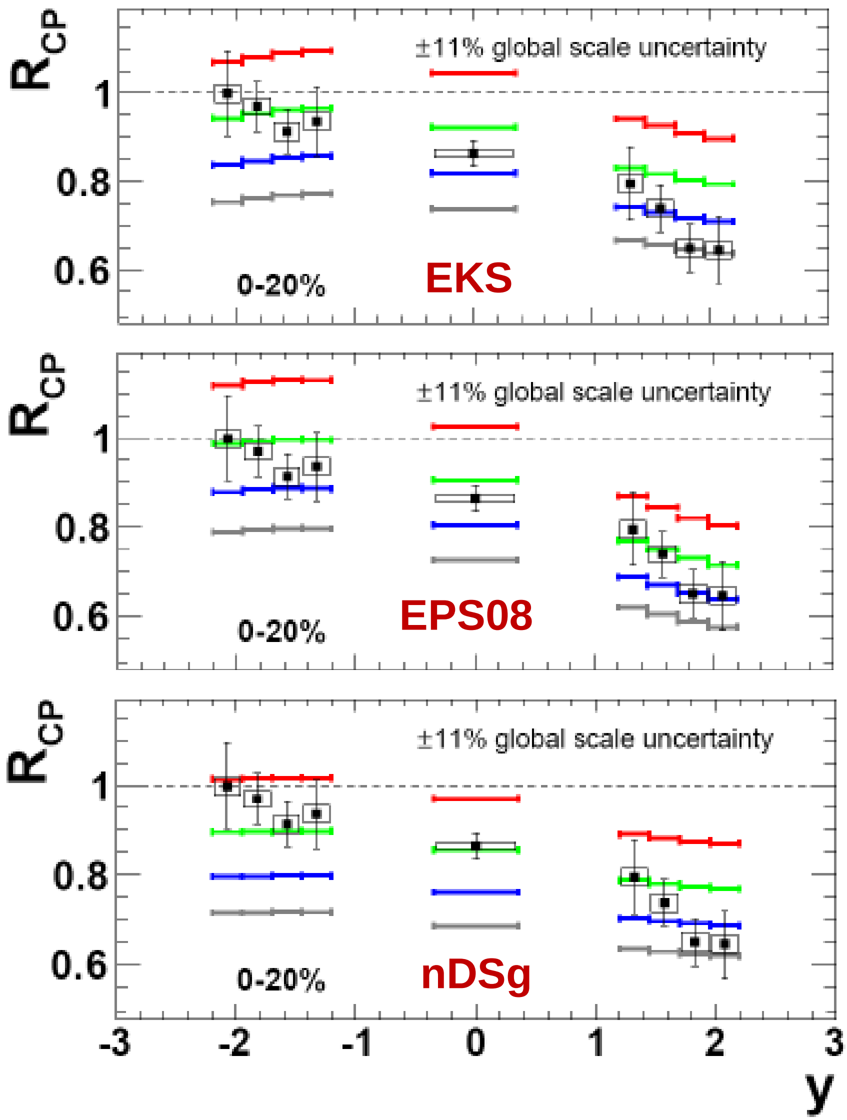
- for CSM like processes, the reaction involved is of type 2→2, with a fraction of the momentum being carried by the third hard gluon (*extrinsic* p_T)

⇨ A different x-region of the (n)pdf is sampled, which affects the suppression pattern.

The position of the anti-shadowing peak is shifted towards higher y;
The effect of shadowing is smeared.

Impact of production mechanism (2)

arXiv:0912.4498



Here, EKS, EPS08 and nDSg shadowing are used, compared to most central 2008 d+Au data.

Various colors correspond to increasing $\sigma_{breakup}$.

As before, the calculations fail to describe the most forward suppression.

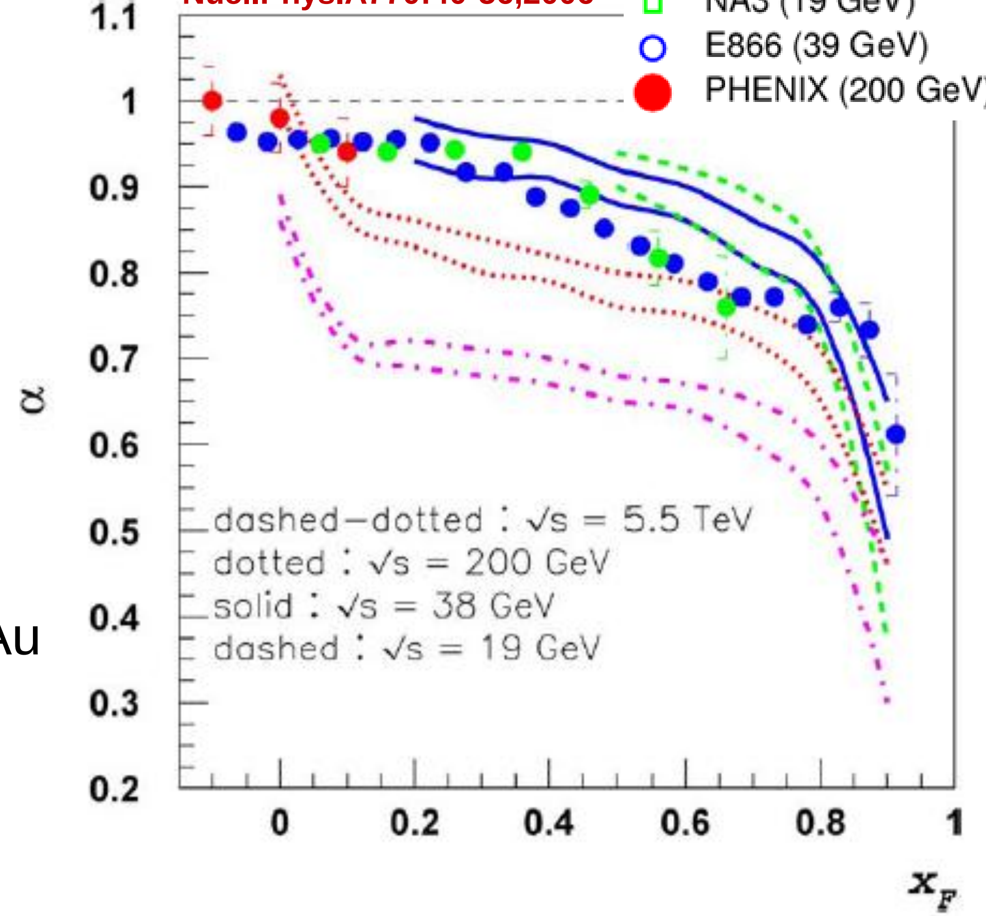
Gluon saturation (3)

CGC formalism aims to explain

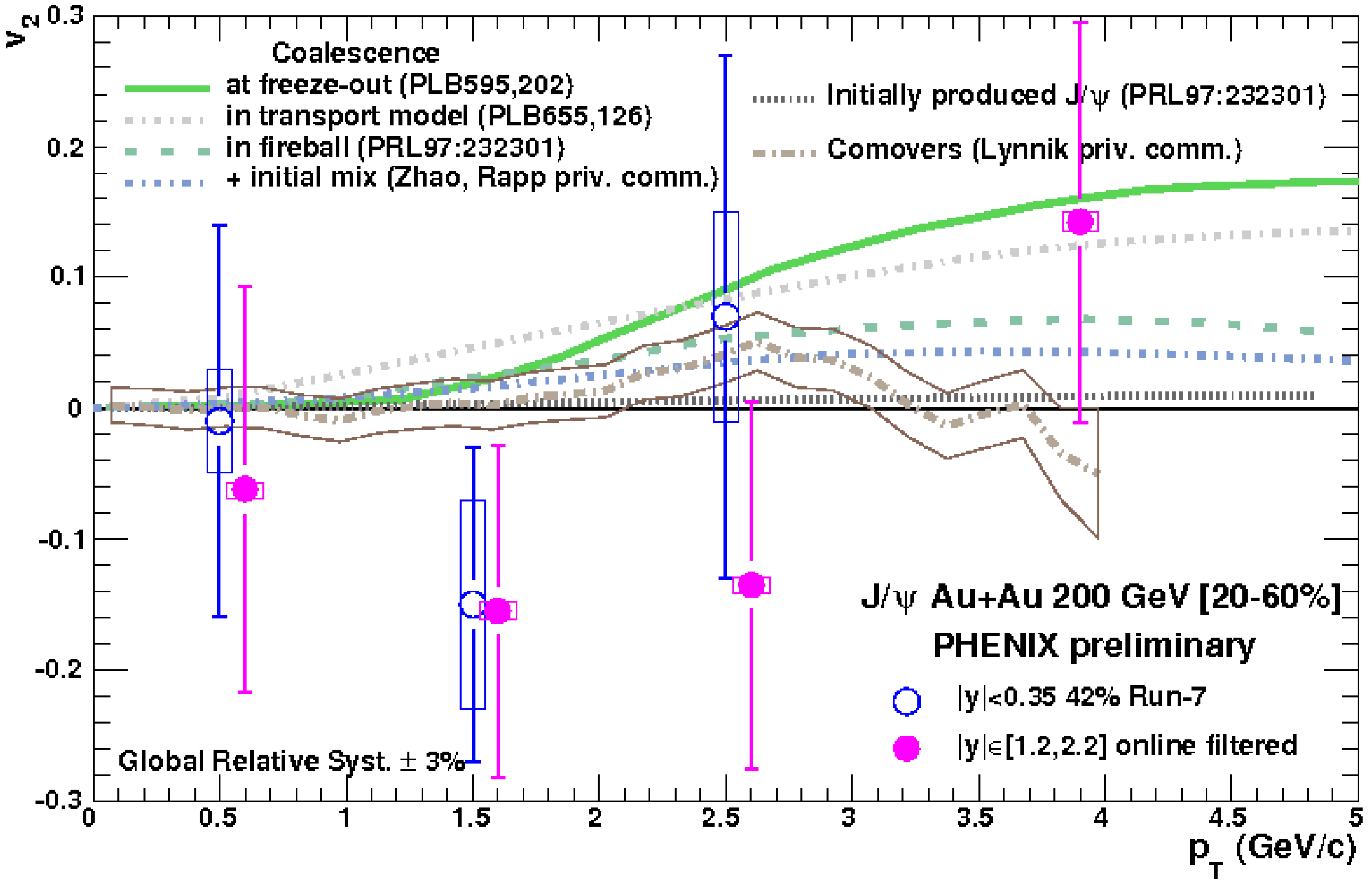
- why x_2 scaling is not observed;
- why approximate x_F scaling is observed, provided that the energy difference between the experiments being compared is not too large

Calculations also available for Au+Au collisions (PRL.102:152301,2009)

Nucl.Phys.A770:40-56,2006



J/ψ elliptic flow



This is a first measurement, at both mid and forward rapidity.

Very limited statistics so that no strong conclusion can be drawn.

Need more data, and detector upgrades.